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SAFETY BRIEF

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Principles of Human Safety*

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Abstract

This paper describes selected concepts from safety and human factors engineering. Important philosophical tools that affect designs are summarized.

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I. INTRODUCTION

A. DEFINITION OF SAFETY

The dictionary definition of safety is technically acceptable: the condition of being free from injury or loss. Its antonym, danger, is defined as exposure or liability to injury, pain or loss. Safety or danger is characterized by only two concepts; "how badly you are hurt" (severity) and "how often you are hurt" (frequency).

B. THE EXACT THEORY OF SAFETY

Everyone in the field of safety accepts as axiomatic that nothing created by man or nature is completely incapable of inflicting harm. Since we are destined to live with some amount of danger, it is reasonable to attempt its quantification. One popular system for doing this takes the form:

Equation 1:	Danger = f(hazard, risk)

The difficulties in applying such a formula to a given machine or system are prodigious, but their contemplation provides important insights into the general problem of safety.

1. Hazard: something that can injure or do damage.

Its magnitude is called severity. No universal measurement exists for severity which has been characterized by economic loss, lost work days and relative ranking on various lists which purport to reflect a hierarchy of human misery beginning with death as the most severe consequence and running down to nymphomania. The subjective nature of severity is illustrated by considering the loss of a hand to a mathematician, a pianist, a person born with only one hand, and a one handed mute person who will no longer be able to sign. Assigning a severity level in such circumstances cannot presently be done within a rational system even though juries do it every day.

2. Risk: the probability of encountering a hazard and receiving an injury.

It is a measure of frequency and can be defined objectively since it involves counting. Unfortunately, data bases from which frequencies can be estimated are rarely available. Even when the federal government has the information required by design engineers, legal barriers preclude its transfer because such information can compromise the rights of potential litigants (tort-feasors).

In special circumstances where the exact magnitude of the hazard is not an issue, risk statistics provide very valuable safety information; e.g., number of deaths or disabling injuries. Judgements on the relative safety of alternate forms of transportation may be based on statistics such as "deaths per passenger mile."

The most important measure of risk is called the *accident frequency rate* (AFR) [Ref. 1] which is defined as the number of disabling injuries per million man-hours.

The National Safety Council carefully monitored the AFR in dozens of industries from 1926 through 1976. The "all industry average" of these statistics forms a benchmark against which safety professionals may judge their efforts. Specifically, the lowest AFR ever attained, 5.99, was achieved in 1961 (See Fig.1). When a given

ACCIDENT FREQUENCY RATE* CHART

*Frequency Rate is defined as the number of disabling injuries per 1,000,000 Man-Hours

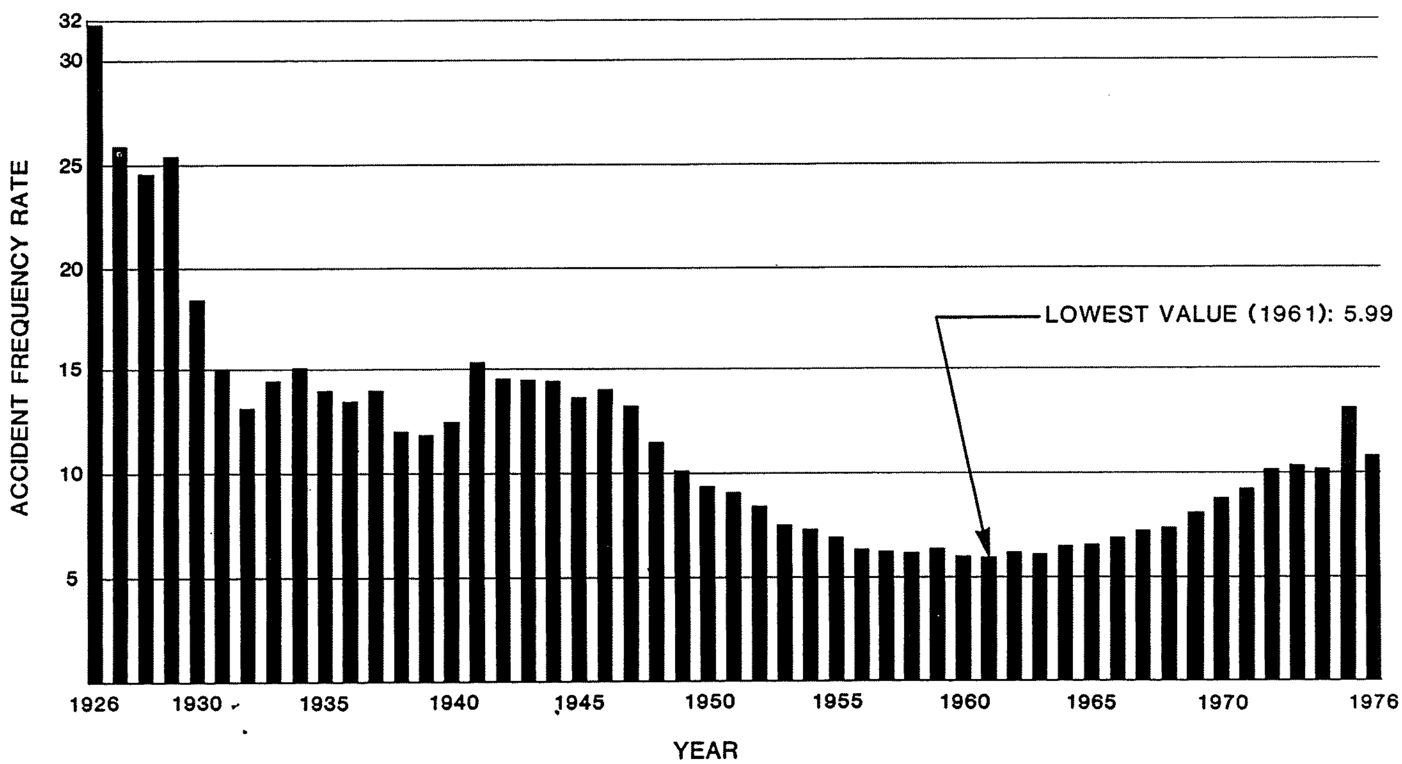

Figure 1. Data is not available after 1976 because the method of compiling accident statistics has changed. However, accident frequency rates have continued to increase.

design has an APR much lower than 6, it means that the safety strategy is moving in the right direction.

3. The Safety Function

Symbolized by the letter f in Equation 1, the safety function represents a presently unknown function or combination of hazard and risk that would represent an acceptable characterization of danger. An enormous amount of research will be required to establish this "safety function." For the time being, we will postulate merely that danger should increase continuously as hazard (severity) increases and as risk (frequency) increases. Further, danger should be zero if either the severity or the frequency is zero. It should be noted that proposals have been advanced that danger be defined as the product of hazard and risk: no research supports this simplistic thesis.

4. Danger

Only the technical definition alludes us, and that is defined by Equation 1. What are the units of danger? Are three units of risk equivalent to one unit of hazard?

Assume that we are capable of computing the danger from Equation 1. What danger level is acceptable, i.e., how safe is safe enough? Unfortunately, nothing in technology can answer this question. The proper domain for questions of this type is "value systems." Such systems reflect the viewpoints of our society and as such may be geography and time dependent.

Important value systems which deal with safety questions are:

a. American National Standards Institute - A consensus value system comprised of all parties substantially concerned with the safety of particular machines;

b. Occupational Safety and Health Administration - A governmental regulatory value system;

c. State Building Codes - Legislative value systems;

d. Case Law - The judicial value system.

In summary, the exact theory of safety involves a subjective component (hazard), an objective component for which no general data base exists (risk), a research component involving an unknown functional relationship between severity and frequency and a value system component (danger). No direct use of this exact theory can be forecast in the near future. On the other hand, it has great merit as an indirect safety tool.

It should be noted that another popular form of Equation 1 uses risk as a function of severity and frequency [Ref. 2]. The multiple definitions of risk are disconcerting and counter-productive and are typical of fundamental problems that compromise progress in the field of safety.

C. COMMUNITY OF USERS

Radically different safety strategies apply to various groups of people such as:

1. Workers who build a product;
2. Installers of a product;
3. Operators;
4. Maintenance personnel; and
5. Bystanders.

Important definitions of a "product defect" involve explicit reference to this community of users. (In Section III.C.2, note how the California Supreme Court refers to the community of "Ordinary Consumers.") Most safety research has been directed toward operation. Recent efforts, however, have begun to focus on maintenance.

II. ASPECTS OF DESIGN PHILOSOPHY

Every engineered system represents a trade-off among at least three criteria: cost, safety and function. Indeed, other requirements may have to be met such as esthetics, light weight or liability resistance, but these are not universal whereas cost, safety and function are.

A. CODE OF ETHICS

Every engineering code of ethics requires that: "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties" [Ref. 3]. Note that welfare includes economic well-being. The code of ethics adds to the normal functional focus of engineering the extra ingredients of cost and safety.

B. SAFETY HIERARCHY

The past four decades have witnessed the emergence of various safety hierarchies which safety practitioners have embraced in their approach to accident prevention. The hierarchies do not arise from a research base; they reflect the experience of safety professionals and safety organizations. An examination of the literature reveals enough similarities among the hierarchies to suggest the existence of a consensus. The safety hierarchy shown in Table I represents the current consensus reflected in the literature [Ref. 4].

The first priority is the elimination of danger. Recall that the word "danger" is taken as a function or combination of hazard and risk. The elimination of a hazard was attempted in the design of lawn mowers by removing the metal blade and substituting a whirling nylon string. An example of risk removal is the use of a central lubricating system. Note that a central lubricating system, which itself is not a safety device, effects the system safety by reducing the number of potentially hazardous locations that need to be accessed during lubrication activities.

The second priority is the application of "safeguarding technology." This includes all safety concepts except warning, training, and personal protection. It includes not only guards and safety devices, but also more abstract notions such as redundancy, structural safety factors and fail-safe design, e.g., the use of shear pins to limit the torque delivered to a power shaft.

The third priority is placement of warning signs and placards on and about machinery. The fourth priority is training and includes verbal and written warnings which appear in instruction manuals and the full range of teaching techniques. The fifth priority is the prescription of personal protec-

TABLE I

SAFETY HEIRARCHY - 1985

FIRST PRIORITY: **ELIMINATE THE HAZARD AND/OR RISK**

SECOND PRIORITY: **APPLY SAFEGUARDING TECHNOLOGY**

THIRD PRIORITY: **USE WARNING SIGNS**

FOURTH PRIORITY: **TRAIN AND INSTRUCT**

FIFTH PRIORITY: **PRESCRIBE PERSONAL PROTECTION**

TABLE II

PRINCIPLES OF PREVENTING WORK-RELATED INJURY*

EXACT SAFETY THEORY	INJURY PREVENTION OBJECTIVE	EXAMPLES	RELEVANT CONTROL PRINCIPLES
ELIMINATE HAZARD	1. To prevent the creation of the hazard.	One-story buildings reducing the need for ladders.	Elimination, Substitution
REDUCE SEVERITY OF HAZARD	2. To reduce the amount of hazard of vehicles.	Reducing speeds.	Process design
	7. To modify relevant basic qualities of the hazard.	Using breakaway roadside poles, Making crib slat spacing too narrow to strangle a child.	Process design
	8. To make what is to be protected more resistant to damage from the hazard.	Making a structure more fire and earthquake resistant.	Process design
ELIMINATE RISK	3. To prevent release of the hazard.	Bolting or timbering mine roofs.	Enclosure
REDUCE FREQUENCY OF EXPOSURE	4. To modify the rate or spatial distribution of release of the hazard.	Brakes, Shutoff valves, Reactor control rods.	Ventilation
	5. To separate in time or space the hazard and that which is to be protected.	Walkways over or around hazards, Evacuation.	Isolation, Administrative controls
	6. To separate the hazard from worker by inter-position of a material barrier.	Operator control booths.	Isolation, Personal protective equipment

*The numbers correspond to eight relevant categories described by Haddon; two additional ones are "after accident" strategies.

tive devices, such as eye protection, hearing protection, and environmental garments.

It should be noted that in spite of the fact that the safety hierarchy in Table I constitutes an important tool for improving safety, it does not rise to the level of a mathematical theorem or a scientific law. This safety hierarchy was born out of consensus, not research, and its general validity can be disproved by numerous counter-examples.

C. DANGER REDUCTION-EXACT THEORY OF SAFETY

The safety hierarchy is qualitative and is thereby restrictive in guiding designers. On the other hand, the exact theory of safety provides useful quantitative directions which follow directly from a desire to minimize danger. Certainly, elimination of hazard or risk gives zero danger. Also, when we minimize hazard or risk we minimize danger. Consider, for example, the well known injury prevention strategy proposed by Haddon [Ref. 5], reorganized along the lines of minimizing severity and frequency in Table II. Note how naturally danger reduction schemes suggest themselves when using the exact safety theory.

D. DOWNSIDE EFFECTS

Safety devices may help you, hurt you, or do nothing. Depending on the character of particular safety devices, different philosophies are available to guide designers in device application.

1. Intrinsic Classification of Safeguarding Systems

If one takes every combination of positive, negative or neutral characteristics of a safety device, seven mutually exclusive and jointly exhaustive categories are obtained as shown in Table III [Ref. 6].

2. Philosophical Positions

From a purely safety point of view—ignoring things such as function, practicability and cost—this classification permits a clear delineation of professional responsibility. Dealing with the most obvious problems first, we would focus on categories VI and VII where devices that compromise public safety are placed on a machine and are without any redeeming or offsetting characteristics. The code of ethics of every engineering society would consider the inclusion of such devices unethical and not in concert with the professional's obligation to protect the public.

Clearly, Type I and II devices, which increase safety without collateral disadvantages, cannot be excluded from engineering systems on the basis of safety alone. Indeed, there are compelling humanitarian, ethical and legal reasons to incorporate such devices when they are feasible, compatible and economically practicable.

Type III safety devices, devices which do nothing, must be rejected. One of the most important objectives of engineering is to minimize cost. It follows that non-functional devices should be excluded from all engineering works. Furthermore, it is unethical to mislead the public and increase cost when no value is delivered.

Certainly, the most provocative devices fall into categories IV and V. Here, the devices themselves create danger. Has an engineer or a manufacturer in our society the right to foreseeably cause harm to individuals for any reason not dictated by the society's value system? For example, can an engineer unilaterally force drivers to wear seat belts in order to save 100,000 lives, knowing that 10,000 people, who would otherwise be unharmed, will be killed by drowning, fire and lower abdominal injuries because they were wearing their seat belts? One cannot find an answer to this question in technology. We must look to the society's value system for guidance.

Perhaps the most unequivocal position taken in the safety literature is the admonition against the use of guards which offer accident hazards of their own. Typical excerpts from this literature, which date from 1916, provide some insight into this philosophy [Ref. 7]:

1980: *Concepts and Techniques of Machine Guarding* (OSHA 3067). Washington, DC, OSHA, 1980.

"What must a safeguard do to protect workers against mechanical hazards? Safeguards must meet these minimum general requirements:.... Create no new hazards. A safeguard defeats its own purpose if it creates a hazard of its own, such as a shear point, a jagged edge, or an unfinished surface which can cause a laceration." pp. 7-8.

1975: *Handbook of Occupational Safety and Health*, Chicago, IL, National Safety Council, 1975.

"It is a cardinal rule that safeguarding one hazard should not create an additional hazard." p. 138.

TABLE III
INTRINSIC CLASSIFICATION OF SAFEGUARDING SYSTEMS

Type I - Devices that always improve safety.
Generally, U-joint shields and PTO guards are of this type.

Type II - Devices that sometimes improve safety and at other times leave the system unaffected.
An example may be an awareness barrier which defines the safe (outside) from the unsafe (inside) region on a piece of farm equipment.

Type III - Devices that always leave the system unaffected.
Adding redundancy to a fail-safe system provides an example of this type.

Type IV - Devices that sometimes improve the safety and sometimes increase the danger of the protected system.
The interlocked guard is usually of this type.

Type V - Devices that sometimes improve the safety, sometimes increase the danger and sometimes leave the system unaffected.
The seat belt is a classic example in this category.

Type VI - Devices that sometimes increase the danger of the protected system and sometimes leave it unaffected.
An example would be an emergency stop control mounted on a tractor drawn cornpicker which invites an operator into an area where he should never be while the machine is running (see Fig. 2).

Type VII -Devices that always increase the danger of the system to be protected.
A "Man Cage" for a mobile crane is an example of a system which legitimizes an unsafe use historically admonished by every crane manufacturer.

1948: *American Standard Safety Code for Power Presses and Foot and Hand Presses*, ANSI B11.1-1948. New York, American National Standards Institute, 1948.

"5.2 General Requirements for Point of Operation Guarding. 5.2.1 Every such device shall be simple and reliable in construction, application, and adjustment. It shall be permanently attached to the press or the die. It shall not offer any accident hazard of itself." pp. 9-10.

The admonition not to adopt safety devices that have a downside applies to individual designers and manufacturers. Such devices, however, are often required (shall) or approved (should) by safety standards and codes. Here, the respective safety organizations represent value systems that balance the upside and downside effects of particular safeguarding systems. If they find the upside sufficiently compelling, permission is granted to use the Type IV or V devices.

E. ZERO MECHANICAL STATE (ZMS)

ZMS [Ref. 8] is a philosophy which applies mainly to maintenance personnel. The act of shutting off and locking out the electrical power disconnect is not sufficient to minimize hazards during maintenance. Other potential sources of energy that may produce a mechanical hazard must also be minimized. For example, evacuating compressed air, lowering suspended loads, relaxing the stored energy of springs and isolating pressurized hydraulic fluids are also necessary procedures for achieving ZMS.

1. Responsibility

In 1975, the ZMS system was introduced into the American National Standard, Z241.1, Safety Requirements for Sand Preparation, Molding and Coremaking in the Sand Foundry Industry [Ref. 9]. In this standard, portions of the responsibility for achieving ZMS lie with the manufacturer, employer and employee. The manufacturer must provide as part of its maintenance instructions a description of the procedure for ZMS. The employer must provide maintenance personnel who have the technical background necessary to understand the information in the maintenance manual and must develop a standard ZMS procedure. The employee must ultimately carry out the ZMS procedures before placing any part of his body into the path of a machine member which normally has the ability to move. When possible, the ZMS should be verified, e.g., by depressing the start button after the electrical power has been locked out to make sure the equipment will not start.

2. Activities Other Than Troubleshooting Maintenance

Persons performing installation, cleaning, adjustment, setup, repair and lubrication must be trained in and observe the ZMS concept of not placing a part of their body into the path of possible moving machine members and not entering a machine until ZMS procedures are satisfied.

3. Troubleshooting

The ZMS concept recognizes the necessity to troubleshoot machinery (problem diagnosis) with the power on, guards removed and protective devices bypassed. However, prior to removing guards or placing a part of the body into the path of a machine element, the equipment must be put into ZMS. Afterwards, the equipment may be observed while under power. Sometimes it is necessary to adjust a machine during powered operation (training conveyor belts); here, special training and background is usually required. Prior to placing the equipment back into production, the original mechanical problem must be repaired and the safety devices replaced.

III. ASPECTS OF ERGONOMICS

Ergonomics, or human factors, is an applied science concerned with the design of facilities, equipment, tools and tasks that are compatible with the anatomical, physiological, biomechanical, perceptual and behavioral characteristics of human beings. Overlapping areas in safety engineering and ergonomics deal with the reduction of personal injuries.

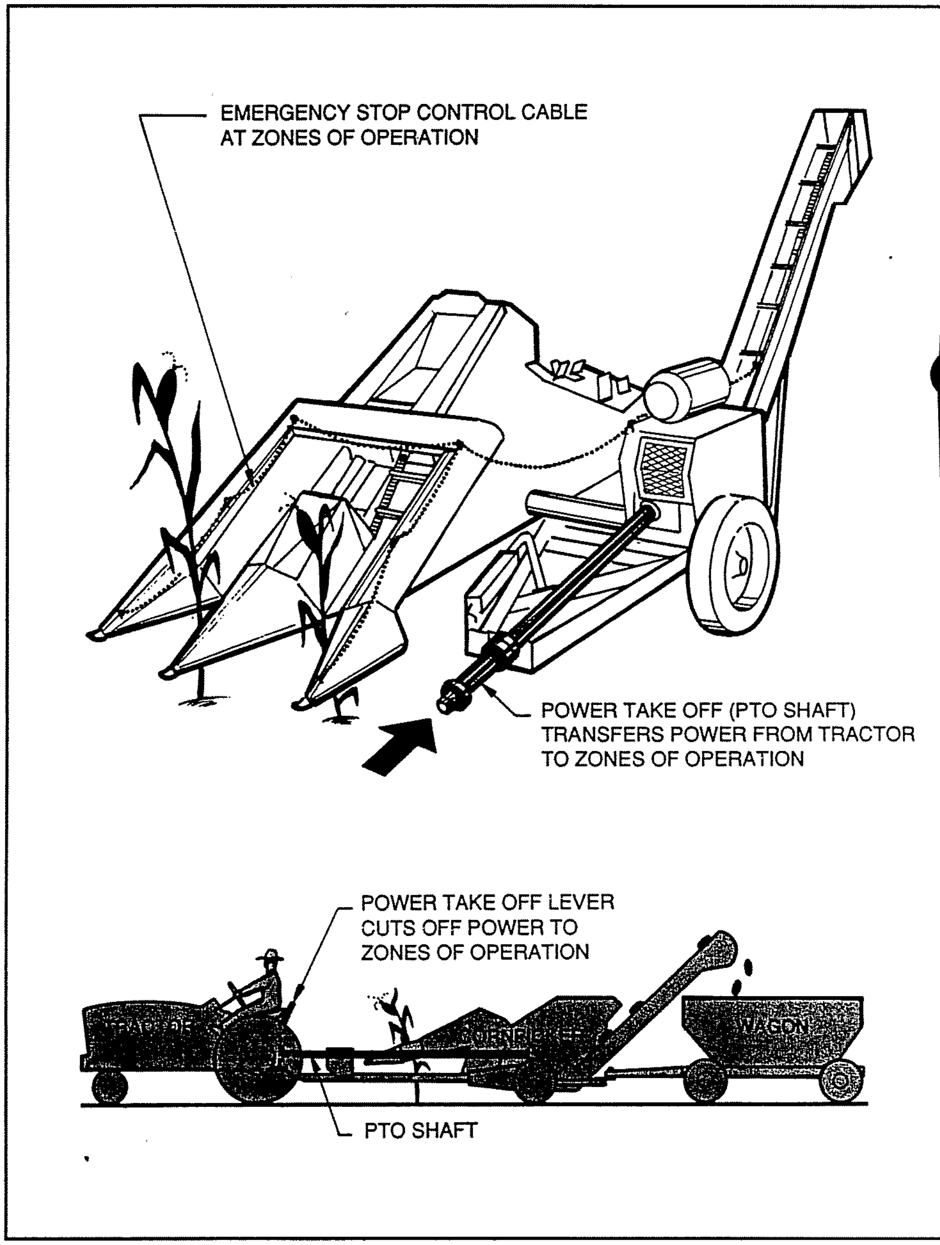

Figure 2.
Tractor-drawn corn picker with controversial Type IV Device, Emergency Stop Control Cable

A. FUNCTIONAL HIERARCHY OF SAFEGUARDING SYSTEMS

In section II.D.1, an intrinsic classification was described which focused on characteristics of individual safeguarding devices or concepts. Here, we are concerned with the relationships among the various safeguarding systems. The initial approach to this relationship classification problem was to establish a sort of pecking order which would allow safeguarding devices to be ranked according to the type of protection offered; Table IV. Application of our initial scheme showed it to be both useful and internally consistent; however, important safety problems seemed to fall outside of its scope. For example, it did not explain why a knife is not unreasonably dangerous or why all but the very young keep their hands out of a Great Dane's mouth. Moreover, the scheme did not account for the very low injury frequency rate associated with the press brake compared to the mechanical punch press.

It became apparent that proper account of a system's safety profile required the introduction of a category which would deal with those safety characteristics inherent in a system. These characteristics, which include simplicity, obviousness, slow motion and widespread user training are ranked under Zero Order Safeguarding Systems in Table IV. All of the Zero Order concepts fall within the discipline of ergonomics.

From the designers viewpoint, zero order systems involve four major man/machine interactions relative to safety: danger recognition, danger control, motivation and human error.

1. Danger Recognition (Perception)

Natural selection, in the Darwinian sense, has produced a community of machine users that recognize immediately certain hazards that are described in the legal literature as "open and obvious" or "patent." Fast moving vehicles, open flames, the in-running nip of a clothes wringer and the reciprocating action of a punch press ram all present hazards that are instantly perceived without training. Neither animals nor aborigines would place their bodies between the closing doors of an elevator. The importance of hazard recognition in safety is brought home when systems are observed in which hazards are hidden, or latent. Young children playing with matches, ingesting tasty and colorful chemicals, touching a "third rail" or darting out into traffic all account for a tragic toll in life and limb. All are examples of man/machine interactions where the community of users does not have the training, experience, or cunning to recognize the hazards. In addition to hazard recognition, personal vigilance also involves risk recognition. For example, the operating status of a machine is normally communicated by visual, auditory or tactile means. Often, electrical shorts provide olfactile cues; contamination of foods is usually revealed by taste.

2. Danger Control

The safety of a machine is greatly enhanced if the user can cope with the dangers presented. This can be accomplished if the user can control either the hazards or the risks.

One of the common ways of dealing safely with hazards is to temporarily suspend them by stopping a machine before placing oneself in jeopardy. This may be achieved using the stop buttons, power-take-off levers or hydraulic valves conventionally incorporated into a machine's control system.

There are man/machine interactions that enable operators to control risks by avoiding hazards or minimizing the probability of encountering them. Speed and directional controls are used by licensed drivers to circumvent accidents, fallen trees and potholes. Construction workers can easily avoid being run over by cranes, concrete spreaders, and asphalt rollers because these vehicles all travel at one-third of walking speed. Knives are considered safe because people can handle them safely thanks to extensive training as children followed by a lifetime of continuous practice.

3. Safety Motivation

Not all people capable of recognizing danger choose to avoid it. In fact, there are people who regularly court or ignore danger: mountain climbers, sky divers, ski jumpers and workers who engage in horseplay or disregard established safety procedures. Legal doctrines such as "assumption of risk" and "contributory negligence" have been used to deny recompense to plaintiffs who were the authors of their own misfortune because they acted in a manner that their community regards as reckless. The ability to recognize danger and the ability to control danger are necessary, but not sufficient conditions to minimize the number of injuries and/or their severity. The desire or motivation to use these two safety tools has a very significant influence on a system's injury frequency rate. Consider, for example, four possible approaches to operating a machine:

a. Maximum Output Method
This is often associated with piecework or bonus compensation. Workers are compensated for the amount they produce which often leads them to stress production over safety.

TABLE IV

FUNCTIONAL HIERARCHY OF SAFEGUARDING SYSTEMS

ZERO ORDER SAFETY SYSTEMS:

Safety properties of a machine or system that derive strictly from man/machine interactions, independent of any safeguarding devices that may be present.

Examples would be the open and obvious danger of the knife, the slow speed of the press brake ram relative to human reaction time, and the simplicity of tin snips.

FIRST ORDER SAFETY SYSTEMS:

Safety devices or concepts that eliminate or minimize a hazard or the exposure to a hazard.

All of the classical punch press safeguarding devices fall into this category: barrier guards, pullback devices and two-hand controls. Note that the first order systems enhance the effectiveness of the zero order systems.

SECOND ORDER SAFETY SYSTEMS:

Devices or concepts used only to enhance the effectiveness of first order systems.

An interlock used as a reminder to keep a guard in place is an example in this category.

THIRD ORDER SAFETY SYSTEMS:

Devices or concepts used to enhance the effectiveness of second order systems.

An instruction plate describing how to test and maintain an interlock is an example in this category.

FOURTH ORDER SAFETY SYSTEMS:

Devices or concepts used to enhance the effectiveness of third order systems.

A part reorder number on the third order instruction plate falls into this category.

HIGHER ORDER SAFETY SYSTEMS:

The extension to higher order systems is self-evident.

b. Least Work Method
Operators who wish to conserve their energy sometimes do things the "easy way" rather than the "safe way."

c. Work Standard Method
Industrial engineers give operators a prescription for achieving a specified output. Sometimes these instructions fly in the face of proper safety practices.

d. Maximum Safety Method
These work schemes minimize danger. It is desirable that a work method simultaneously produce maximum safety and output with the least demand on the operator. This goal can rarely be achieved in the real world and often it is safety that is compromised. An extensive literature exists dealing with risk taking [Ref. 10, 11, 12] and with motivation [Ref. 13, 14, 15].

4. Human Error

On a personal level, a human error is an act which is counter-productive with respect to the person's private or subjective intentions or goals. From the safety engineer's viewpoint, human error is defined as any human action revealing a deviation from the action that would have averted a dangerous event or reduced its seriousness. The science of human error makes a useful distinction between slips and mistakes. Slips occur when a person's actions are not in accordance with the actions actually intended, whereas mistakes are actions performed as intended but with effects which turn out, immediately or at a later stage, not to be in accordance with the person's intended goal. The nature, level and factors associated with human errors in the workplace that may be influenced by designers are described in Table V.

Ergonomic sources provide many of the tools required to minimize the adverse consequences of human error in the workplace. Ergonomists usually subdivide the field into information ergonomics and physical ergonomics. Information ergonomics is concerned with the collection, display, sensing, and processing of information. Physical ergonomics is concerned with worker size, strength, capabilities for motion, and working posture.

Ergonomists use a number of techniques that include the evaluation of the transmission of information between the machine and the worker (link analysis), discovery and evaluation of system failures (critical incidence analysis), detailed examination of the sequence of actions taken by workers (task analysis) and analysis of situations that may arise from unprogrammed events or human errors (contingency analysis). Ergonomists also make extensive use of anthropometric data concerning the physical dimensions and capabilities of the human population. In addition, the techniques of biomechanical analysis are used to measure expected physical stresses encountered by parts of the body while performing work tasks [Ref. 16].

TABLE V

ENGINEERING CHARACTERISTICS OF HUMAN ERROR

Nature of Errors
Omission
Inappropriate action
Transposition
Actions performed too late
Actions performed too soon

Level of Task When Error Occurred
Sensing, perception, detection
Information processing, interpretation
Action, control execution

Error Factors
Task characteristics
Workstation characteristics
Work time
Work organization
Training
Procedure format
Individual factors

B. THE DEPENDENCY HYPOTHESIS

Safeguarding systems may be introduced to perform specific safety tasks, to comply with some code or standard, to liability-proof a machine or as a by-product of a functional device.

When safety systems are imposed on a device, alterations in the man/machine interface occur that may go well beyond the intended effects. The Dependency Hypothesis provides a unifying thesis under which observations of safety system effects can be made in an organized manner. Our ultimate concern is that the side effects of safeguards do not compromise the overall system safety.

1. Statement of The Dependency Hypothesis:

Every safety system gives rise to a statistically significant pattern of user dependence.

This may also be stated in legal jargon: "User dependence on safety systems is foreseeable."

The Dependency Hypothesis does not speak to the issue of whether or not reliance on safety systems is good or bad; it suggests only that secondary effects exist as a consequence of behavior modification in the presence of such systems. The evaluation of safety systems must include consideration of these secondary effects which sometimes compromise the entire safety program. From the designer's viewpoint, the Dependency Hypothesis manifests itself in two cogent areas; introduction of misuse and substitution to lower safety profiles.

Some people misuse safety devices by performing tasks that differ from the designer's intent. Examples include misuses as controls, misuses in kind, and misuses in magnitude. There are three reasons why these misuses intrude on the design process:

a. Sellers/Manufacturers have a duty in most states not only to design products for normal use but also for reasonably foreseeable misuses;

b. New hazards may be introduced through the misuse of safety devices; and

c. Compromising secondary effects may outweigh the benefits of the safety devices.

The most provocative behavioral characteristic associated with the normal use of safety systems is substitution. It appears in three areas:

a. The substitution of safety systems for personal vigilance;

b. The substitution of one safety system for another; and

c. The substitution of authoritative direction for personal wisdom and experience.

There is nothing intrinsically wrong with these substitutions, but they must be examined in the light of their potential for mischief. New systems must not be inferior to the originals. Furthermore, substitutions which introduce new hazards must be measured against the prevailing philosophy relative to dangerous safeguarding devices or against operable value systems such as consensus standards, regulations, or the judicial value system.

2. Misuse

User dependence on safety systems commonly results in three forms of system misuse: misuse as control systems, misuse in kind, and misuse in magnitude.

a. Misuses as Control Systems
Many safeguarding systems protect by overriding normal machine operation. They may, for example, freeze motion, prevent start-up, return members to home base, or temporarily remove hazards. As users become familiar with the characteristics of these safety systems, a certain percentage of them will use the safeguards to control the machines.

i. Elevator Door Problem
Almost the entire community of elevator users knows that conventional elevators

have a safety device in the leading edges of the doors which will stop and/or reverse the closing door when the door edge contacts a passenger. It has become a pervasive misuse of the "safety edge" to employ it as a control device for manually interrupting the closing door to accomodate passengers arriving late.

ii. Light Curtains:
A Standardization Dilemma
An extension of the classical "electric eye," a light curtain acts as a sentinel in front of a point-of-operation. Penetration of the curtain signals the machine to stop so that no harm will befall the operator. The light curtain is routinely misused to interrupt the cycle to reposition parts, clean off debris or perform routine maintenance.The light curtain gives rise to a special type of misadventure involving standardization. The misuse of the curtain as an emergency stop control becomes habitual. When operators are transferred to machines not equipped with light curtains, their automatic emergency response is to reach into the machine! This is analogous to the habit of using one's foot to catch small parts that have dropped. This useful predilection fails decisively when the foot automatically catches a heavy die or crankshaft.

b. Misuses in Kind
Designers are variously shocked, amused, bewildered and relieved at the alternative and additional uses which are suffered by safety devices. For example, the defensive characteristics of the modern football helmet are often turned into offensive weapons. The use of helmets for spearing was not originally anticipated by the helmet designers and will cause wearers neck injuries culminating in paraplegia and quadroplegia.

c. Misuses in Magnitude
To provide structural integrity, engineers incorporate "safety factors" or "factors of ignorance" into their designs to account for uncertainties in the assumed loading, shortcomings in workmanship, approximations in their design methodology, variability in material properties and the effects of time, wear and alterations. The use of safety factors almost always leads to designs which are stronger than required by the functional specifications of the problem. Safety factors invariably increase the cost of the final design and very often increase the size and weight. These effects are endured and demanded by society as a guarantee that the final design will perform at least as well as expected. Unfortunately, users come to depend on the extra capacity built into products and compromise their reliability by pushing them beyond their rated performance levels. Some classic examples follow.

i. The Hoisting Problem
A one-ton crane hook is proportioned to achieve a five ton ultimate capacity. This corresponds to a safety factor of five (5). As they use the hooks, many users will divine their excess capacity and take advantage of it. When such misuse results in tragedy, the adversary legal system will suggest that the misuse was reasonably foreseeable and that the safety factor of five (5) is too low in spite of the fact that it meets professional safety code specifications for crane hooks. Such arguments, when abetted by the natural compassion of juries, will frequently lead to verdicts against hook manufacturers.

Repeated punishment by the courts will eventually compel manufacturers to make their products "liability-proof" by adopting higher and higher safety factors. Thus, a one-ton hook may achieve an ultimate capacity of ten (10) tons, i.e., a safety factor of ten (10). Unfortunately, users will continue to depend on the ever increasing excess capacity of the hooks, accidents will result, suits will be filed and the process will continue without end.

ii. The Grinding Wheel Problem
Most grinding wheels are proof-tested by overspeeding them by 50 percent at the time of manufacture.This safety system removes all the weak members from the statistical population of wheels and assures that the survivors have a strength level at least 50 percent greater than the wheel rating.

In use, the faster the grinding wheel, the faster material is removed. This motivates users to overspeed the wheels in spite of maximum speed instructions marked on them. These users depend on the built-in 50 percent overspeed capability.

3. Expected Use
Engineers and lawyers do not always have the same definition of "expected use" of a safety system. To an engineer, "the expected use" is the use(s) he intended for the safety system. To a lawyer, the "expected use" is the use(s) expected by the community of users - what a "reasonable person" would do with it under like or similar circumstances. The lawyer's definition incorporates what people really do rather than merely what they're supposed to do. Note that the two definitions are not mutually exclusive. The engineer's intended use is probably one of the uses of a "reasonable person."

There is nothing cerebral in the supposition that users will depend on safeguarding systems to perform in a normal manner. On the other hand, it is provocative to contemplate the possible harm such dependence can lead to in the face of unreliability, ineffectiveness, and sabotage. The behavioral changes resulting from such dependence are discussed in the following paragraphs.

a. Decreased Vigilance
Without safeguarding systems, users of machinery protect themselves by diligently applying their natural abilities to recognize and control danger. The safety literature has recognized the transference of such personal vigilance to dependence on safety devices. For example, increased production is claimed to result from elimination of an operator's fear of the machine in the presence of safety devices [Ref. 17].

b. Obedience
Safety information is communicated in various forms that are regarded as authoritative. Accordingly, significant numbers of people will rely on written, audible, and graphic warnings, instructions, codes, standards, manuals, and safety publications. Verbal admonitions from supervisors or instructors are often very compelling methods for modifying or reinforcing safety behavior.

Misadventures stemming from obedience to safety misinformation are particularly insidious since they arise from conscientious behavior. The following communication shortcomings highlight the problem:

i. Incomplete Information
The Occupational Safety and Health Administration requires that skylights have the "capability of supporting the weight of a 200 lb. man." One manufacturer meticulously satisfied the language of this requirement by applying 200 lbs. of sand uniformly distributed over the surface of their 4 ft. by 4 ft. skylight. Unfortunately, the skylight collapsed when a roofer stepped onto it.

ii. "A Little Bit of Knowledge"
Consumer power table saws are the most dangerous of woodworking machines. In an attempt to "liability-proof" their machines, some manufacturers have incorporated a safety instruction plate containing a half dozen or so admonitions. This carries with it the implicit suggestion that strict adherence to the safety instructions qualifies one to operate the table saw safely.

When the safety plate is compared to the safety training program administered by typical high school woodworking shops, the plate's inadequacy is immediately apparent and frightening.

iii. False Information
One of the classic cases of misdirection arises from the use of safety status lights that indicate a danger when lit. When the bulb burns out, a safe condition is falsely indicated.

iv. Dangerous Instructions
OSHA provides written instructions for testing the upper hoist limit switch on overhead

and gantry cranes. Their written procedures are dangerous:

29 CFR 1910 179(k)(1)(ii): *"The trip setting of hoist limit switches shall be determined by tests with an empty hook traveling in increasing speeds up to the maximum speed. The actuating mechanism of the limit switch shall be located so that it will trip the switch, under all conditions, in sufficient time to prevent contact of the hook or hook block with any part of the trolley."*

29 CFR 1910 179(n)(4)(i): *"At the beginning of each operator's shift, the upper limit switch of each hoist shall be tried out under no load. Extreme care shall be exercised; the block shall be 'inched' into the limit or run in at slow speed. If the switch does not operate properly, the appointed person shall be immediately notified."*

Note that the tester and bystanders are in jeopardy when the procedure reveals a defective limit switch by dropping a hoist block on them.

c. Change in Safety Philosophy
The imposition of safety devices into a system may radically alter the prevailing safety strategy. Consider, for example, the introduction of Emergency Stop Controls (ESC's) on a corn picker (See Fig. 2).

Since corn pickers are completely automatic, only maintenance functions such as cleaning, unclogging, and lubrication require "hands on" work. Such work can safely proceed using ZMS (Zero Mechanical State) concepts (Section II.E). These provide the most modern and advanced safety maintenance philosophy.

Before starting to maintain the corn picker, the farmer disengages the Power-Take-Off (PTO) lever isolating the motion of the entire corn picker. He then disembarks from the tractor and may work in safety. The PTO lever is one of the most popular and most reliable controls on the tractor and provides almost continuous check-out and training.

Accidents have occurred when farmers have neglected to disengage the PTO before performing maintenance and it has been proposed that Emergency Stop Controls (ESC's) such as pull cords be provided at the maintenance points. There are three types of user expectations engendered by emergency stop controls (ESC's):

i. Prevention - They will prevent injuries.

ii. Mitigation - If any injury occurs, the ESC will lessen the severity of the injury.

iii. Invitation - The area near the ESC will be safe when the machine is running. (There are controls there; controls are meant to be activated by people; therefore the control areas must be safe areas.)

The heart of the ZMS approach is to prevent accidents. This may be contrasted with the proposed use of ESC's which cannot eliminate injuries which occur faster than human reaction time. This is particularly devastating in view of the fact that a significant number of farmers will accept the invitation of the ESC. They will be lured into the zones of operation to perform tasks with the corn picker running and with no possibility that the ESC can fulfill the promise of preventing injury.

C. THE COMPATIBILITY HYPOTHESIS

Safeguarding systems may be missing from a machine for a variety of reasons that are dominated by human factors considerations:

1. Removed to increase production
2. Left off for ease of maintenance
3. Were uncomfortable
4. Were worn out or damaged
5. Left off for esthetic reasons
6. Not reinstalled on machine after maintenance
7. Machismo
8. Horseplay
9. Not shipped originally
10. Lost during use
11. Cannibalized to repair other machines
12. Had undesirable side effects (Types IV & V; see Table III)
13. Removed to improve safety (Types VI & VII; see Table III)
14. Were incompatible with other safety systems
15. Sabotage

Note that some of the reasons for removing or circumventing the safeguards are related to utility (Examples 1, 2, 3, 5, 11) and some are concerned with safety (Examples 12, 13, 14). In these cases, the following hypothesis provides guidance to the designer in dealing with this important safety problem:

1. Statement of
The Compatibility Hypothesis:

The larger the perceived improvement in utility compared to the perceived increase in risk, the greater will be the motivation to circumvent a machine's safeguarding system.

Note that risk is taken as the probability of encountering a hazard already present on the machine.

2. Barker v. Lull Engineering Co.
A risk/utility criterion for judging the safety of a machine was introduced in 1978 in a product liability decision:

Barker v Lull Engineering Co. 573 P.2d 454 (1978). In this case, the Supreme Court of California stated that, "a product may be found defective in design, so as to subject a manufacturer to strict liability for resulting injuries, under either of two alternative tests...

a. A product may be found defective in design if the plaintiff establishes that the product failed to perform as safely as an ordinary consumer would expect when used in an intended or reasonably forseeable manner.

b. A product may alternatively be found defective in design, if the plaintiff demonstrates that the product's design proximately caused his injury and the defendant fails to establish, in light of relevant factors, that, on balance, the benefits of the challenged design outweigh the risk of danger inherent in such design."

Among the "relevant factors" the jury may consider when weighing the benefits of the design against the risks, in the second test, are:

"(i) the gravity of the danger posed by the challenged design;

(ii) the likelihood that such danger would occur;

(iii) the mechanical feasibility of a safer alternative design;

(iv) the financial cost of an improved design;

(v) the adverse consequences to the product and to the consumer that would result from an alternative design."

Since the Barker case, many other states have adopted the risk/utility criterion in their products law and in each state it is assumed that the judges and juries possess the ability to compare alternative designs on the basis of risk and utility. The compatibility hypothesis implies that operating personnel, who possess greater familiarity with their machines, exercise the same type of judgement requested of jurors.

3. Design Consideration
To illustrate how designers may benefit from the compatibility hypothesis, consider the following:

a. Multifunction Guards
If guards are designed with many functions, their removal may lead to a very small or negative increase in utility. For example, a power transmission guard that also serves as an oil bath for gears cannot be left off the machine since the machine cannot function without lubrication.

b. Redundancy
An operator may not perceive an increase in risk when a backup safeguard is removed. Meat grinders, for example, have two First Order safeguards; the stomper and spider (barrier) guard. Large increases in the feed throat capacity are achieved by removing

the spider guard; concomitant increases in risk are not perceived by operators who always use the stomper. Here, manufacturers have embraced a number of antisabotage techniques to minimize guard removal.

False Impressions

The compatibility hypothesis operates on the basis of perception; not fact. If operators harbor a false impression that may compromise their safety, the designer may decrease circumvention by communicating correct information. For example, operators ignore admonitions not to wear jewelry because they don't understand the severity or frequency of the danger warned against.

D. "K.I.S.S."

"Keep It Simple, Stupid" - This is an old admonition that requires designers to adopt simplicity as a design goal. Almost all of the traditional engineering attributes seem to benefit from simplicity, e.g., cost, function, maintainability, weight, operator training, safety, reliability, etc. Unfortunately, "Simplicity is the most deceitful mistress that ever betrayed man" [Ref. 18]. Furthermore, achieving simplicity is anything but simple.

Indeed, the notion of simplicity appears throughout the literature of ergonomics. Task difficulty is a common reason for conducting a task analysis to determine the level and type of skills and knowledge required for performance. When too many tasks comprise an activity or when too little time is allotted which unduly paces production, the term "task overloading" is often applied. Task overload appears regularly in scheduling, load stress, message display and human error analysis. Simplification is often its cure.

E. DECOUPLING

The notion of decoupling is that a designer should not require an operator or maintenance person to place his well-being in the hands of another person. It is difficult enough for the right hand to consistently know what the left hand is doing, let alone know and track what another actor is up to. The graphic arts industry has successfully addressed the problem of multiple operators working simultaneously on large machines. Each workstation on a printing press incorporates an Inch/Stop/Safe control which precludes all motion of the press when set to the "safe" position. There are three lights at each workstation. A green light indicates that someone has set the machine on "Safe". An amber light glows only at those workstations that are set in the "Safe" mode. A red light at each station signals that the press is in "running condition". Furthermore, when the press is started up in either the jog or run modes, a time delay is encountered during which interval an audible alarm is given. Complete standardization has been the rule for several decades [Ref. 19].

F. WARNINGS

The goal of warning signs is to enhance safety by modifying human behavior in order to reduce the severity and frequency of injuries. Most warnings have little or no effect on safety; some compromise it [Ref. 20]. The success of the media and the advertising industry in influencing behavior does not have its counterpart in safety signs. Communication theory has not addressed warnings and almost no research has been directed toward this challenging concept. On the other hand, a vast literature on warning signs has arisen from the law and consensus which is filled with misinformation and misdirection.

A few results that may prove useful in guiding designers are briefly discussed:

1. Warning Signs - The Safety Hierarchy

Recall that the third priority of the safety hierarchy is to use warning signs. It is regarded as more important to try to eliminate the danger or safeguard it.

2. The Rule of Seven, Plus or Minus Two

On complicated machines such as automobiles and aircraft, there are hundreds of hazards that cannot be eliminated or technically safeguarded. Even if it is possible to invoke the third priority and produce suitable warnings for these individual hazards, the sheer number of warnings destroys their effectiveness. The majority of the population can recall only five to nine written items in a series. In communication theory this is called the "Rule of Seven, Plus or Minus Two" [Ref. 21]. Where large quantities of safety information must be communicated, warning signs cannot be used and one must resort to training.

3. Colors and Human Factors

Ergonomic research has determined the most desirable colors and color combinations [Ref. 22]:

a. Visibility of opaque colors under similar light conditions:

1. Yellow is the most luminous and visible.
2. Orange and red-orange hold maximum attention value.
3. Blue is likely to be hazy and indistinct.

b. Most legible color combinations are listed in order:

1. Black on white (most legible)
2. Black on yellow (most attention gained)
3. Green on white
4. Red on white
5. White on blue
6. Combinations of pure red and green or red and blue are not satisfactory.

Note that red is not prominent. About 8% of the male population and 0.05% of the female population has difficulty in discriminating certain colors; red is a problem color. The popularity of red as a safety color is entirely due to its association with danger (fire, blood).

4. Warning Label Shapes

Riley, Cochran and Ballard [Ref. 23] studied 19 different geometric shapes of warning labels. Their results show the triangle on its vertex is the preferred warning indicator. Furthermore, shapes that appear unstable tend to be preferred as warnings. It should be noted that the triangle on its base, not its vertex, is rapidly becoming the international safety symbol. In the United States, it's used for slow moving vehicles and as a general safety alert. Especially note that the triangle on its base and containing an exclamation mark is the safety alert symbol for agricultural equipment [Ref. 24].

5. Warning Sign Clutter and Seriousness

Because of liability-proofing, it is rare that a modern machine does not contain a plethora of warning and caution signs. These rarely deal with hidden dangers; mostly they warn against hazards that are open and obvious and serve only to liability-proof the machine. On the other hand, from a safety point of view, they frequently compromise the machine. For example, too many warning signs produce clutter and increase the probability that none of the signs will be read, including the really important ones. Furthermore, it is difficult to encourage people to take safety signs seriously when most of them are silly — Expect the Unexpected, A Clean Machine is a Safe Machine, Obey all Signs and Don't Place Hands Under Blade.

These may be contrasted with warnings dealing with hidden dangers - Danger-20,000 Volts, Machine May Start Unexpectedly in Automatic Mode, Press May Stroke After Motor is Shut Off, Wait Until Flywheel Has Stopped Before Servicing and Beware of Guard Dog.

A rule of thumb for detecting silly warning signs is to examine the opposite warning, e.g., "Keep Machine Dirty and Obstructed". If the opposite of the intended warning sounds ridiculous, then the sign is probably unnecessary because common sense dictates the intended admonition.

6. Guidelines

Gomer [Ref. 25] has compiled a listing of current guidelines recommended by consensus standards, federal regulations, in-

TABLE VI

1986 GUIDELINES FOR WARNINGS

I. Does the warning command attention:
   A. Is the warning conspicuous?
      1. Is the warning clearly visible?
      2. Have attention-directing symbols and pictographs been used?
      3. Has the appropriate signal word been used?
      4. Has appropriate color coding been used?
      5. Is the size of the warning scaled to the dimensions of the product?
      6. Has a border been used to isolate the warning?

II. Does the text of the warning:
   A. Identify the hazard?
   B. Indicate the degree of risk and the consequences of exposure?
   C. List conditions under which the product is likely to be a hazard?
   D. List precautions and means of avoiding the hazard?
   E. Identify actions to be taken if exposure to the hazard occurs?
   F. Employ clearly understandable, familiar language?
   G. Provide a message that:
      1. Is accurate?
      2. Uses active voice?
      3. Is affirmative and avoids "fudge" words?
      4. Creates the appropriate concern for safety and perception of the risk by incorporating an urgency that is commensurate with the danger?
      5. Is concise?
   H. Take into account the persons to whom the warning is addressed?
   I. Conform to common standards, regulations, and practices?

III. Is the warning placed in reasonable proximity to the hazard?

IV. Is the text readable?
   A. Has a foreseeability analysis considered reading distance, illumination levels, and other factors?
   B. Have label life and degradation been considered?
   C. Have typographic features been considered?

dustry handbooks, government recommendations, textbooks and journals (Table VI).

This guideline list can be compared to the scope of the Draft January, 1987 ANSI Z535.4, Product Safety Signs and Labels:

"A product safety sign or label should alert persons to a specific hazard, the degree or level of hazard seriousness, the consequences of involvement with the hazard, and how the hazard can be avoided."

It is noteworthy that ANSI and most modern safety authors use "Signal Words" to designate "danger" or the degree of hazard seriousness. The signal words for product safety signs are Danger, Warning and Caution. They are characterized as follows:

a." DANGER" indicates an imminently hazardous situation which, if not avoided, will result in death or serious injury. The signal word is to be limited to the most extreme situations.

b."WARNING" indicates a potentially hazardous situation which, if not avoided, could result in death or serious injury.

c. "CAUTION" indicates a potentially hazardous situation which, if not avoided, may result in minor or moderate injury. It may also be used to alert against unsafe practices.

To contrast the results of consensus and research, the work of Leonard, Matthews, and Karnes [Ref. 26] suggests that the signal words had no effect on the perception of risk:

"The experiment concerns the problem of responding appropriately to warnings. Some organizations, such as the military and the American National Standards Institute have adopted particular meanings for certain signal words. The population at large is not trained in these respects. Therefore, it is not known how they interpret different signal words. In keeping with the assumption that the stronger the warning, the more likely it will be heeded, an effort was made to determine how the population in general differentiates levels of warnings. The study examined population stereotypes for various signal words. Contrary to some studies (of Karnes and Leonard, 1986), no differences were found in ratings of perception of risk to different signal words. Further, size of the signal word and color of the signal word had no effect on perception of risk. Statements of consequences of disregarding the warnings and type of risk situation did affect rated perception of risk" [Ref. 27].

Another study by Ursic [Ref. 28] reached the same conclusion - size, color and signal words are not effective safety parameters:

"This study using 91 undergraduates attempts to alleviate this void through an experiment in which the design and presence of a safety warning are systematically varied. The presence of a warning is found to have a positive impact on an individual's perception of the effectiveness and safety of a brand. The use of a pictogram, the strength of a signal word and the use of capital letters in a safety warning are found to have little effect on perception of a brand or on memory of safety information."

Perhaps the safety profession can learn something from automotive designers who indicate the fullness of the fuel tank by several schemes that require no words. A thermometer is used by many fund raising organizations to indicate relative closeness to their goals. Such methods could indicate relative danger (death to no injury) without training or standardization. Furthermore, such schemes are infinitely variable as opposed to settling for three signal words.

7. Warning Sign Philosophy

The 1941, ASA Z35.1, Specifications for Industrial Accident Prevention Signs, stated their scope as:

"These specifications apply to design, application and use of warning signs or symbols intended to indicate and, in so far as possible, to define specific hazards of a nature such that failure to so designate them may lead to accidental injury to workers or the public, or both or property damage."

Note that all hazards are not addressed; only the hidden hazards. This scope uses the ability of workers to recognize hazards and in so doing minimizes the number of required warnings. With time, the safety profession expanded their scope to the status indicated in the preceding section. It is obvious that too much information is being required especially in multiple hazard situations.

A simple and effective philosophy can be formulated by combining ideas contained in the various ANSI scope statements. To aid in "attention arresting", signal words or more advanced notions can be used to indicate the relative danger magnitude. It is important to characterize the hazard so that it may be avoided and, also, to communicate the level of harm to make the sign more persuasive. To do this, we must identify the hazard and give some notion of its magnitude which can best be done by describing the consequence of contacting the hazard. Here, we would state that a designer should:

a. Identify the hazards where failure to do so will lead to injuries.

b. Describe the consequences associated with the hazard where failure to do so will lead to injuries.

As an example, it is not necessary for adults to be told the consequences of touching a busbar with a potential of 20,000 volts. On the other hand, informing workers that continued exposure to chemicals produces accumulated long term effects may persuade them to seek proper ventilation.

As a final goal, a warning sign should provide danger control which may include both avoidance techniques and remedies after exposure. This may be stated as follows:

c. Describe methods for avoiding or controlling the hazard where failure to do so will lead to injuries.

d. Describe remedies if failure to do so will exacerbate the injury.

In situations where the activities in (a), (b), (c) and (d) are not required, a warning sign should not be used. Most warning signs will not require all four components.

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Safeguard Evaluation Protocol–

A Decision Tree for Standardizing, Optionalizing, Prohibiting, Ignoring, Enhancing, or Characterizing Safeguards

by Ralph L. Barnett* and Steven R. Schmid**

Abstract

A decision protocol is developed for assessing whether a candidate safeguard should be offered as standard or optional equipment or whether it should be enhanced, prohibited, ignored, or just characterized. Satisfaction of the protocol is a sufficient condition for satisfying the code of ethics for engineers, extant codes and standards, the Intrinsic Classification of Safeguards, and the Dangerous Safeguard Consensus. Decisions that do not satisfy the protocol violate one or more of these safety philosophies. This decision making process intellectually disposes of the judicial position that a manufacturer has a nondelegable duty to include safety devices with his machines. It further challenges the advocacy pronouncement that "safety should not be optional."

I. INTRODUCTION

Presently, no methodology exists for rationally dealing with the conditions and circumstances under which candidate safeguards can be accepted or rejected. Decisions are generally grounded intuitively with guidance from codes, standards, and industry practice. By and large, sensible judgements flow from this approach; however, it is not error free and it does display randomness and inconsistency. Moreover, it fares rather poorly when the decision making procedures are challenged in courts or other tribunals.

In our development of a protocol we have adopted a principle enunciated by Albert Einstein, "Everything should be made as simple as possible, but not simpler." To this end, a small number of concepts are described which represent required relationships among safety entities (necessary conditions). These are assembled into a decision tree that will simultaneously satisfy the engineering code of ethics, value systems such as codes and standards, the Intrinsic Classification System, and the consensus position on safeguards that introduce new dangers.

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For additional examples see:
Barnett, Ralph L. and Steven R. Schmid, "An Application of the Safeguard Evaluation Protocol," in *Safety Engineering and Risk Analysis 1995 (SERA-Vol. 4)*. New York, American Society of Mechanical Engineers, 1995, pp. 9-16.

We thought it might be instructive to present the decision tree and run through a couple of examples before explaining its development. In Fig. 1, each element of the safeguard adoption decision tree has been numbered in its upper corner for tutorial purposes.

Example 1. Rear Seat Air Bag - Year 1994

For this first example, enter Fig. 1 at [1] and move down to value systems. Rear seat air bags are not presently used. Furthermore, there are no codes, standards, statutes, or regulations that require, recommend, or prohibit the use of air bags in the rear seat of an automobile; therefore, move to [4]. Assume for the purpose of this example that the candidate air bag has no downside; it either *helps or does nothing* from a safety point of view. Move to [9] and then to [12] since the automobile is a uni-functional machine. Because the air bag has no effect on the function of an automobile, we move to [16]. Air bags are quite expensive and will adversely effect cost, [19]. Proceeding to [24] which is the branch of *Unreasonable Economic Impact* associated with [9], we find three courses of action; the air bag for the rear seat may be offered as optional equipment [27], may not be offered [28], or advice on the characteristics and outsource availability may be given to vehicle users [29].

Example 2. Machine Mounted Two Hand Hostage Controls - General Purpose Press Brake

Referring to Example 2 in Fig. 1, move from [1] to [2] since this safety feature is approved by the American National Standards Institute, Safety of Press Brakes, ANSI B11.3-1982. Although the standard approves of two-hand hostage controls, it neither requires or recommends them; hence move to box [8]. A general purpose press brake is multi-functional and not dedicated. Furthermore, its use is not known to the machinery manufacturer; therefore, move to [14]. Two-hand controls have many limitations, e.g., operators cannot reach them when bending large sheets or when the trailing edges must be supported throughout the forming operation. Furthermore, a bent workpiece may invade the space where the two-hand controls are located. For these reasons we proceed to [18]. From [18] we may select [22] and offer the two-hand controls as an optional accessory or we may proceed to [21] and inquire into its market status. Two-hand hostage controls are widely available [26]. This fact is known to the community of press brake users who are all familiar with the characteristics of these devices [30]. Consequently, we may choose to drop any further consideration of these controls [32], or we may advise customers of their functional and safety properties, their cost and their availability from outside sources [33].

II. CONCEPTS AND DEFINITIONS

A. Suppliers

The term supplier will be used in this paper to represent manufacturers, fabricators, builders, distributors, retailers, and others in the chain of commerce who supply hardware in the form of systems, machines, or machine components. A procedure is developed to enable suppliers to proactively evaluate candidate safety features. The evaluation of safety systems normally falls within the purview of manufacturers and not distributors. There are, nevertheless, two reasons for including distribution entities in our scope.

First, they may be compelled by law to assume the responsibilities and liabilities of a manufacturer. This frequently happens when manufacturers are absent because they have gone out of business, are insolvent, or are shielded by international law.

Second, suppliers often have input information related to the exact use of machines by their customers. This knowledge may impose duties upon them.

The methodology developed in this paper is not applicable to regulatory agencies, code or standard writing bodies, individual equipment users, or their employers.

B. Safeguards/Safety Features

These terms will be taken to represent safety notions in the broadest sense. In addition to safety devices and contrivances, candidate safeguards may include safety concepts such as proof testing, preventive maintenance, and safety factors; they may be workplace procedures or training programs or they may be safety communication systems such as safety colors, warning signs, and safety manuals.

C. Dangerous Safeguard Consensus

Perhaps the most unequivocal and widespread position taken in the safety literature is the admonition against the use of safeguards which introduce hazards of their own. Typical excerpts from this literature, which date from 1916, provide some insight into this philosophy.[1] For example:

1994: "General Requirements for All Machines," 19 CFR 1910.212 (a) (2). Washington, DC, OSHA, effective August 27, 1971.

"General requirements for machine guards: Guards shall be affixed to the machine where possible and secured elsewhere if for any reason attachment to the machine is not possible. The guard shall be such that it does not offer an accident hazard in itself."

1982: *American National Standard for Machine Tools - Power Press Brakes - Safety Requirements for Construction, Care and Use*, ANSI B11.3-1982.

"6.1.4.1 Point of Operation Guards. Every point-of-operation guard shall meet the following design, construction, application, and adjustment requirements:

(1) It shall prevent entry of hands or fingers into the point of operation by their reaching through, over, under, or around the guard.

(2) It shall, of itself, create no pinch point between itself and moving machine parts."

1975: *"Handbook of Occupational Safety and Health,"* Chicago, National Safety Council, 1975.

"It is a cardinal rule that safeguarding one hazard should not create an additional hazard." p. 138.

1943: C.M. Macmillan, "*Foremanship and Safety*," New York, John Wiley, 1943.

"In considering a machine guard we must realize that it has to give 'tops' in protection and it must not interfere with operation. Also, care must be taken that in guarding against one hazard we do not create another." p. 46.

D. Value Systems

The admonition not to adopt safeguards that have a safety downside applies to individual designers and manufacturers. This prohibition is specifically stated in most of the standards, codes, or statutes yet these very standards, codes, and statutes, regularly demand, recommend, or permit safety features with dangerous side effects such as automotive seat belts or falling object

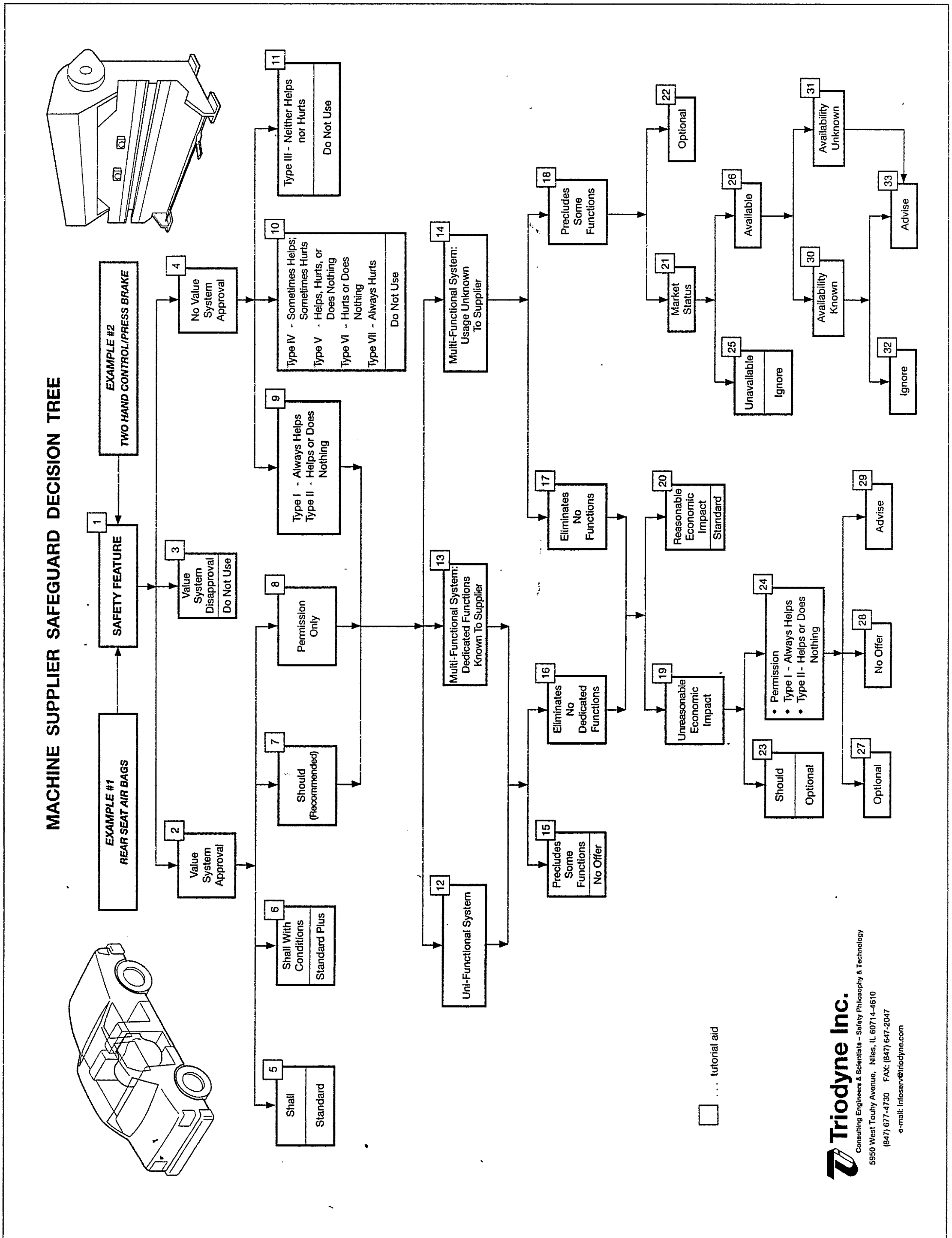

Figure 1. Machine Supplier Safeguard Decision Tree

protective structures on forklifts. There is no contradiction; engineers, designers, and manufacturers are not allowed to make judgements that hurt people even when the benefits are substantial, but value systems are.

A value system is defined as "the system of established values, norms or goals existing in a society."[2] Some of the more important ones that deal with safety issues are:

a. American National Standards Institute - A consensus value system comprised of all parties substantially concerned with the safety of a particular machine.
b. Occupational Safety and Health Administration - A government regulatory value system.
c. State Building Codes - Legislative value systems.
d. Case Law - The judicial value system.
e. Industry Practice.

Occasionally, there will be some dispute among value systems, at which time the relative merits of the positions must be judged. Usually, the more stringent requirements are accepted by a responsible party. It is not unusual for standards to include disclaimers such as "should any of the requirements of this standard conflict with federal, state, or municipal regulations, such conflict shall not invalidate other sections of this standard."

The very nature of value systems bears directly on the act of approval. When applied to the use of safeguards, value systems provide five levels of consent: demand, conditionally demand, recommend, permit, and reject. The following categories reflect these consent states using more familiar nomenclature. The boxes next to the key words indicate their appearance on the associated decision tree shown in Fig.1.

Shall: [5] Codes, standards, and statutes generally demand action with the word "shall" denoting a mandatory requirement. In our decision-making procedure, value system "demands" are held inviolate regardless of their effectiveness.

Shall With Conditions: [6] Sometimes demands carry additional warnings or requirements. For example, the demand for a rollover protective structure on a farm tractor carries with it the mandatory requirement for a seat belt. Together they represent a rollover protection system (ROPS).

Should: [7] Standards generally use the word "should" to denote a recommendation that is a sound safety practice which is not mandatory. For this reason, codes which often carry the force and effect of law, do not use "should." OSHA has expunged the word "should" from their regulations.

Permission Only: [8] Documented permission to use a specific safeguard may be found in some standards that neither demand (shall) nor recommend (should) them. Power press or press brake standards, for example, provide users with a menu of safeguard candidates which may be used in conjunction with a production system consisting of a press, dies, infeed system, off loading (parts and scrap) system, and safety system. Undocumented permission usually involves the accepted practice of a particular industry. The associated community of users tacitly concur that a particular safeguard has an acceptable safety value when there is widespread adoption and continuous use of the safety feature. Many of the safeguards used in printing presses and bakery equipment are undocumented and even state-of-the-art.

Disapproval: [3] Disapproval is the prohibition of a safeguard. It is not unusual for the Food and Drug Administration to preclude the use of certain medicines. The Environmental Protection Agency (EPA) has published codes that play an equivalent role by banning certain chemicals. For example, carbon tetrachloride can no longer be used in fire extinguishers and chlorofluorocarbons (Freon) cannot be used to eliminate the flammable characteristics of aerosol products. The Consumer Product Safety Commission prohibits fireproofing general-use garments with asbestos.

E. Engineering Code of Ethics

The first entry in the code of ethics of every engineering society requires that:

"Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties."

There are two points that should be emphasized. First, the duty of an engineer derives from an obligation to harness technology for the benefit of mankind. And second, welfare includes economic well-being. Welfare is defined as "a state characterized especially by good fortune, happiness, well-being or prosperity."[3]

Technical duties arise from the continually changing demands of society and take the form of independent functional requirements or specifications. They are not variables in the design process. Indeed, candidate safeguards that interfere with functional specifications must be rejected. The code of ethics imposes three additional conditions on the functional requirements - safety, health, and welfare. On the other hand, the code is silent on other properties such as those related to religion, history, and esthetics. One can recall that Ladybird Johnson championed a beautification program that effected the design of highway structures and power transmission poles. Such esthetic considerations are outside the purview of engineering, whereas, safety and cost control are major preoccupations of the profession.

F. Intrinsic Classification of Safeguards

Safeguards, under specific circumstances, may help you, hurt you, or do nothing. If one takes every possible combination of these positive, negative, and neutral characteristics, one obtains seven mutually exclusive and jointly exhaustive safeguard categories as shown in Table 1.[4] From a safety point of view, ignoring things such as function, practicability, and cost, this classification permits a clear delineation of professional responsibility. The most obvious problems are categories VI and VII where safeguards that compromise public safety are placed on a machine and are without any redeeming or offsetting characteristics. The code of ethics of every engineering society would consider the inclusion of such safeguards unethical and in conflict with the professional's obligation to protect the public.

Clearly, Type I and II safety features, which increase safety without collateral disadvantages, cannot be excluded from engineering systems on the basis of safety alone. Indeed, there are compelling humanitarian, ethical, and legal reasons to incorporate such safeguards when they are feasible, compatible, and economically practicable.

Type III safeguards, safety features that do nothing, must be rejected. One of the important objectives of engineering is to minimize cost. It follows that non-functional devices should be excluded from all engineering works. Furthermore, it is unethical to mislead the public and increase cost when no value is delivered.

Table I

INTRINSIC CLASSIFICATION OF SAFEGUARDING SYSTEMS

Type I -	**Safeguards that always improve safety.** Generally, power transmission guards are of this type.
Type II -	**Safeguards that sometimes improve safety and at other times leave the system unaffected.** An example is an awareness barrier which defines the safe (outside) from the unsafe (inside) region on a piece of equipment.
Type III -	**Safeguards that always leave the system unaffected.** Adding redundancy to a fail-safe system provides an example of this type.
Type IV -	**Safeguards that sometimes improve the safety and sometimes increase the danger, of the protected system.** The interlocked guard is usually of this type.
Type V -	**Safeguards that sometimes improve the safety, sometimes increase the danger, and sometimes leave the system unaffected.** The seat belt is a classic example in this category.
Type VI -	**Safeguards that sometimes increase the danger of the protected system and sometimes leave it unaffected.** An example would be an emergency stop button mounted on a slitting line recoiler unit which invites an operator into an area where he should never be located while the machine is running.
Type VII -	**Safeguards that always increase the danger of the system to be protected.** A "Man Cage" for a mobile crane is an example of a system which legitimizes an unsafe use historically admonished by every crane manufacturer. The philosophical positions arising from the intrinsic classification of safeguards are summarized in boxes [9], [10], and [11] of the decision protocol in Fig. 1.

Certainly, the most provocative safeguards fall into categories IV and V. Here, the safety features themselves create danger. As we have seen, a value system must balance the upside and downside effects of a particular safeguard. If they find the upside sufficiently compelling, permission is granted to use Type IV and V systems.

G. The System

In those cases where no value system has approved a candidate safeguard, its classification may require that we examine its relationship to the system under consideration. We observe in Fig. 1 that only three types of safeguards pass through the value system screening: those that are recommended [7] or permitted [8] or those that have no negative side effects [9]. There are two different approaches for handling such safeguards depending on whether the system's use is known or unknown. Uni-functional [12] and dedicated systems [13] are always known to their suppliers; general purpose multi-functional systems [14] are used in ways not revealed to the system's designers and distributors.

When suppliers know or, in the exercise of reasonable prudence, should know how a system will be used, it is straightforward to determine if the candidate safeguard precludes some functions of the system [15]. Such safety devices should not be offered since the welfare of the public is not served by prohibiting system functions the public desires.

In multi-functional systems where the use is unknown to suppliers, it is straightforward to determine whether a candidate safeguard will preclude some expected (as distinguished from foreseeable) functions of the system. Multi-functional machines are purchased specifically because they are general purpose in character and their value to users lies, in part, in their ability to use any of the expected functions. Safeguards that eliminate some expected functions [18] change the very nature of the system desired by the public or the community of users. These safety features must not be made standard equipment because of their adverse functional effects.

If a candidate safety feature can contribute to the system's safety during some of its operations, the public welfare is served when the supplier aids the user in the acquisition of the safeguard. This is certainly accomplished when the supplier offers the candidate safety feature as optional equipment [22]. Sometimes marketplace information is valuable [21]. Unknowledgeable users [31] may benefit from information defining when a safeguard may be used, how it may be used, and how it may be obtained by in-house construction or outsourcing [33]. When the community of users is already knowledgeable about the candidate safeguard [30], no enlightenment is required [32] although one may still volunteer such service [33]. If the candidate safeguard is unavailable in the marketplace [25], a decision to ignore terminates the process.

Dedicated and general purpose systems utilize the same screening process when no dedicated [16] or expected [17] functions are circumscribed by the proposed safeguard. Having passed the safety and functional requirements, the economic impact of the candidate safety feature must be evaluated. Recall that the spirit of the engineering code of ethics requires that welfare also be held paramount.

H. Economic Impact

Safeguards usually increase the system's cost. If the economic impact of a candidate safety feature is reasonable there is a clear mandate to adopt it as standard equipment [20]. Unfortunately, there is no exact protocol for determining reasonableness which may ultimately be a jury question if the efficacy of the safeguard is adjudicated.

Sometimes a candidate safety feature can be affected by a change or substitution that does not effect cost. Not infrequently, it may actually save money by increasing efficiency. For example, a manual centralized lubrication station eliminates maintenance exposure to moving parts while reducing lubrication time to a few seconds. Pressure relief valves not only eliminate explosion hazards to personnel, they protect pressure vessels and surrounding equipment from damage and destruction.

Some of the factors that should be considered in judging the economic impact of a proposed safeguard are:

1. Safeguard Cost

The absolute cost of a safety device or procedure can be stated together with its downstream implications for distributors, users, and the ultimate consumers of the system's production output. The cost is often presented as a percentage of the overall system cost. Judgements are easiest in extreme cases, e.g., the cost of available safety devices for a general purpose wood shaper is 300% greater than the cost of the machine.

2. Maintenance Cost

Safety devices wear out, break, go out of calibration, are bypassed, or are regularly examined as part of a preventive maintenance program. The associated cost of maintaining the candidate safeguard must be included in economic impact studies.

3. Certification Cost

Theme parks are required to regularly certify the safety devices on their amusement rides. Certain applications of light curtains on power presses may require regularly scheduled certification by qualified independent organizations. The cost of such certification must be included in economic impact studies.

4. Production Cost

Safeguards often increase the unit cost of the associated system's output by slowing machines or increasing the number of steps in the production process. Movable gate guards on power presses typically slow down production; higher prices follow. The through-put on meat grinders with safety throats or spider guards is often only 25% to 50% of the unguarded discharge rate.

5. Competition

A great many machines are treated like commodities and are procured by purchasing agents on the basis of "lowest price" alone. If a single manufacturer includes a unique safeguard, his cost increases may price him out of the market. The playing field is no longer level. Many municipalities have laws requiring them to accept the "lowest bid". Gigantic road building contracts are lost by a few thousand dollars on a half billion dollar bid. The point of these two examples is that *small differences between large numbers* can exert a disproportionate effect on a product's acceptance. A safeguard's cost may have a disastrous economic impact on a manufacturer.

6. Societal Cost

Inhibiting the production of vital products because of safeguard related inefficiency may carry with it an unacceptable societal cost, e.g., failing to produce a vaccine in a timely manner.

The inclusion and retrofitting of ground fault circuit interrupters (GFCI) on every electrical outlet in the U.S. would demonstrably save a significant number of lives every year. The cost of implementing such a program is so staggering that only bathrooms and kitchens *in new construction* are considered for GFCI by present value systems. Most rational evaluations of such safeguards rest ultimately on the monetary value of a human life. The courts have severely punished manufacturers who have had the temerity to publish their valuations of human life and limb. A more promising approach to the problem is to establish the cost of saving a life. If you figure it would cost 5 million dollars to prevent the electrocution of one person by adopting a full GFCI program you have achieved an unacceptable societal cost.

If the economic impact of a proposed safety feature is judged unreasonable [19], there are two situations to be considered. The first involves safeguards that are recommended by a value system in spite of their economic shortcomings. These should be made optional equipment [23]. The second involves safeguards that display redeeming safety advantages even though they are not recommended by a value system and have an unacceptable economic downside [24]. These candidates require no specific action on the part of their supplier [28] who, nevertheless, may voluntarily offer them as optional equipment [27] or advise their customers about their safety characteristics and market availability [29].

III. EXAMPLES

Candidate safeguards are evaluated in this section to familiarize the reader with the structure of the decision tree. The various examples make it clear that some of the steps in the decision process are very sophisticated. An understanding of safety side effects is essential to the classification of safety features, but, just as in the field of medicine, they may be difficult to forecast. Establishing the economic impact of a proffered safeguard may be a serious undertaking; establishing its reasonableness may defy analysis.

Example 3: Woodworking Table Saw

Among the various guards available for table saws, the slitter mounted guard is most often supplied as standard equipment; it permits *through-cuts* on any size workpiece. The guard is illustrated in Fig. 2 where it is observed that the slitter stands in the kerf that is cut in the workpiece. If *non-through cuts* are required, there is no through kerf and the slitter prevents passage of the workpiece beyond its leading edge. Examples of some *non-through cuts* are: da-do, cove, rabbets, grooves, panel raising, and resawing. The slitter mounted guard is fully or partially removed from the saw whenever non-through cuts are required.

To guarantee that the slitter mounted guard will be used during through-cutting, it has been proposed that the guard be interlocked so that the saw will not rotate when the guard is removed or is otherwise out of guarding position. Interlocking on saw guards is not called for or even described in woodworking codes and standards. Although it is not used in practice, it is not precluded by any value system. Consider the application of the decision tree to the saw guard interlock where we will presume that all the classical safety deficiencies of interlock technology have been cured (See Fig. 3).

We observe that the hypothetical candidate should either be ignored or offered as optional equipment. In reality a full safety analysis of such an interlock would reveal:

- It is foreseeable that the guard will be raised as an alternative method of shutting off the machine (Dependency Hypothesis).[5,6]
- Because of the low reliability of interlocks, they must be tested at the beginning of every shift; this is usually done by raising the guard during operation.
- It is foreseeable that a raised guard will be substituted for proper lockout procedures during maintenance and blade changing.

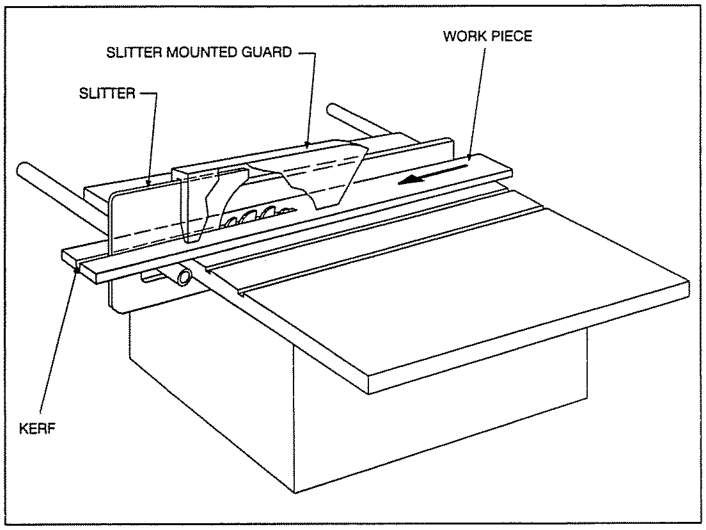

Figure 2. Slitter mounted guard without anti-kickback

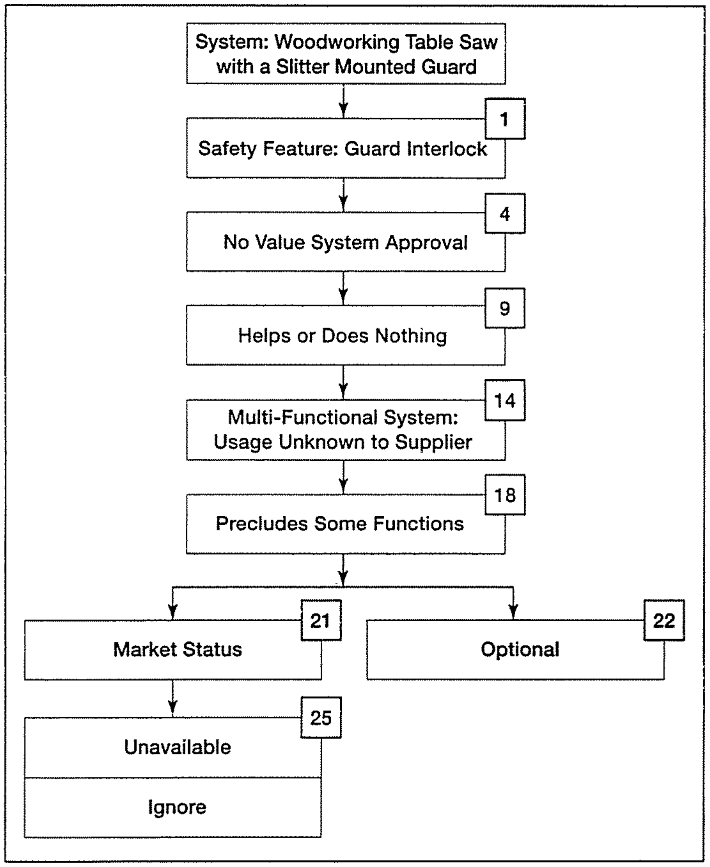

Figure 3. Decision process for woodworking table saw with a slitter mounted guard

- A pattern of interlock bypassing can be forecast with the attendant safety problems (Compatibility Hypothesis).[7]
- The interlock inhibits the adoption of other guard types that are superior to the slitter mounted guard in various applications.

This analysis would classify the safeguard as a Type V device (helps, hurts, or does nothing) not a Type II (helps or does nothing) and the decision tree will move from [1] to [4] to [10] where it terminates in the decision *Do Not Use*.

Example 4. Warning Signs

Some warning signs on ladders, agricultural equipment, lawn mowers, and electrical devices are required by codes and/or standards. For such straightforward applications of the decision tree, one moves from [1] to [2] to [5] where the warning sign is required to be standard equipment.

If the candidate safeguard is an "On Product Warning Sign" to be applied to an ordinary sharp knife, several value systems bear on this simple situation:

- American Standards Association, Specification for Industrial Accident Prevention Signs, ASA Z35.1-1941; (1.1) Scope: "These specifications apply to design, application and use of [warning signs] or symbols intended to indicate and, insofar as possible, to define specific hazards of a nature such that failure to designate them may lead to accidental injury to workers or the public, or both."
- Standard Practice: Ordinary knives carry no warnings.
- Judicial Value System: Most states require that latent, not patent, hazards be identified and characterized by warning signs.

These value systems do not decree that hazards be addressed that are open, known and understood by the community of users.

The decision protocol for the knife would proceed from [1] to [4] to [11] where it mandates that the warning not be used. A warning dealing with the propensity of a knife to injure by cutting or stabbing is a Type III safeguard that neither aids nor detracts from the cause of safety. The warning does not transmit information that is unknown to the user; it has no safety downside such as clutter since no other warnings are found on knives.

Our final warning sign candidate is for on an extension ladder. Here, it is proposed that users be informed that large dogs can destabilize ladders by jumping against them. Certainly no value system would consider warning of such an obvious hazard. Even in those states that require warnings on open and obvious hazards, one would argue that the hazard is not reasonably foreseeable and that therefore no safety value is obtained. Because there are already three dozen warnings on an extension ladder, each new one adds to the clutter and diminishes thereby the conspicuity and impact of the other signs. Hence, the candidate warning is a Type VI safeguard that hurts or does nothing. The decision tree would then proceed from [1] to [4] to [10] where it advises against using the warning.

Example 5. Grinding Wheel

Proof testing is a safety concept that is used to eliminate weak elements from a statistical population. If grinding wheels, for example, are speed tested to failure, their fracture speeds will exhibit a significant scatter. For a seven inch diameter straight abrasive wheel rated at 6000 rpm the proof or test speed is 9000 rpm as specified in ANSI B7.1-1988. This standard requires 100% speed testing for all wheels six inches in diameter or larger. If their rated speeds are faster than 5000 rpm, the test speed is 50% greater. Under Exceptions (7.1.4) the standard states "Wheels that need not be speed tested are wheels less than 6" diameter."

Consider the application of the decision tree to the proof testing (safety feature) of a four inch diameter abrasive wheel (system). Here the standard gives permission to use proof testing without compelling (shall) or recommending (should) its use. Making the unrealistic assumption that the cost of proof testing is not significant, we obtain the following decision path shown in Fig. 4.

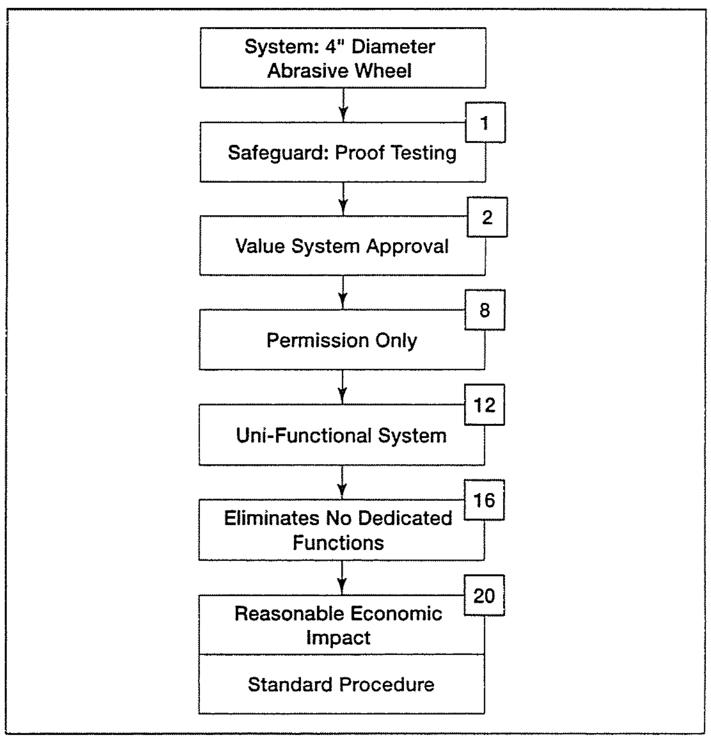

Figure 4. Decision process for a 4" dia. grinding (abrasive) wheel

In this case the proof testing procedure would be adopted as a standard safety feature on four inch diameter wheels. On the other hand, a realistic analysis would recognize that because small wheels are inexpensive, the cost of speed testing a wheel represents a significant cost increase that will certainly price the wheel out of the market. The resulting protocol logic is exactly the same as shown in Fig. 1 for Example 1, the rear seat air bag. Substituting the proof testing safety feature into Box [1] we obtain the same three safeguard adoption choices: Optional [27], No Offer [28], or Advise [29]. The authors would select No Offer [28] since 4" diameter wheels constructed to industry standards will, within a reasonable degree of scientific certainty, never fail the proof test; no safety value is delivered but the cost is increased.

Example 6. Mobile Crane

Three countermeasures have been proposed to eliminate the shock and electrocution hazards associated with power line contacts between the boom, load line, or crane protuberances. They are, respectively, cage-type boom guards, insulating links, and proximity warning devices (See Fig. 5). The phrase "construction management" will be used to describe other countermeasures such as de-energizing transmission lines, visibly grounding or insulating them, erecting physical barriers to preclude power line contact, and maintaining a minimum clearance between the lines and any part of the crane or load.

Referring to paragraph 5-3.4.5 (b) in the safety standard ASME/ANSI B30.5-1989 for Mobile and Locomotive Cranes, we find the following reference to the three "crane electrocution devices:"

"(b) If cage-type boom guards, insulating links, or proximity warning devices are used on cranes, such devices shall not be a substitute for the requirements of (a) above, even if such devices are required by law or regulation. In view of the complex, invisible, and lethal nature of the electrical hazard involved, and to lessen the potential of false security, limitations of such devices, if used, shall be understood by operating personnel and tested in the manner and intervals prescribed by the manufacturer of the device."

Note that the "requirements of (a)" are the construction management procedures previously described.

For purposes of the decision tree, the standard gives permission to use the "three crane electrocution devices" *if* construction management controls are in place, *if* operating personnel are aware of the limitations of the devices so that the potential of false security may be lessened, and *if* the devices are tested in the manner and at intervals prescribed by their manufacturers. The three devices are Type V safeguards that help, hurt, or do nothing for the cause of safety. When the three crane electrocution countermeasures are inserted into the decision tree without the three "ifs" [1], no value system permission is granted and we would move to [4] and then [10] where we would be prohibited from using them. On the other hand, when the three devices are evaluated on the basis that the three "ifs" are satisfied, the steps to be followed are shown in Fig. 6.

Here, we observe that a choice must be made relative to the reasonableness of the cost of the three devices. If judged reasonable, the three devices are standard equipment; if not, the authors would make the choice of not offering the devices [28], because of their downside safety characteristics.

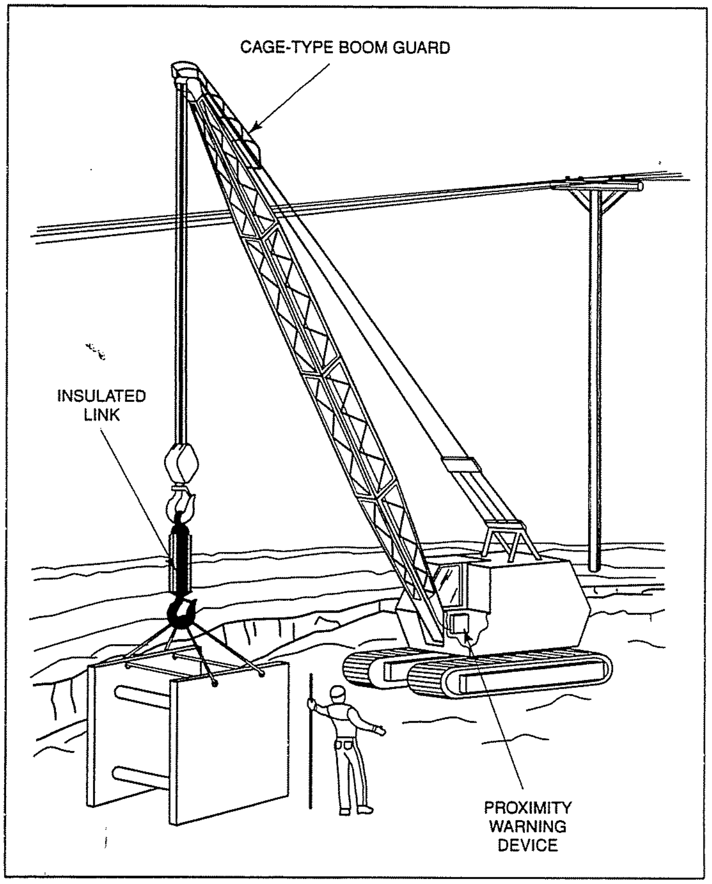

Figure 5. Electrocution and shock safeguards for moblie cranes

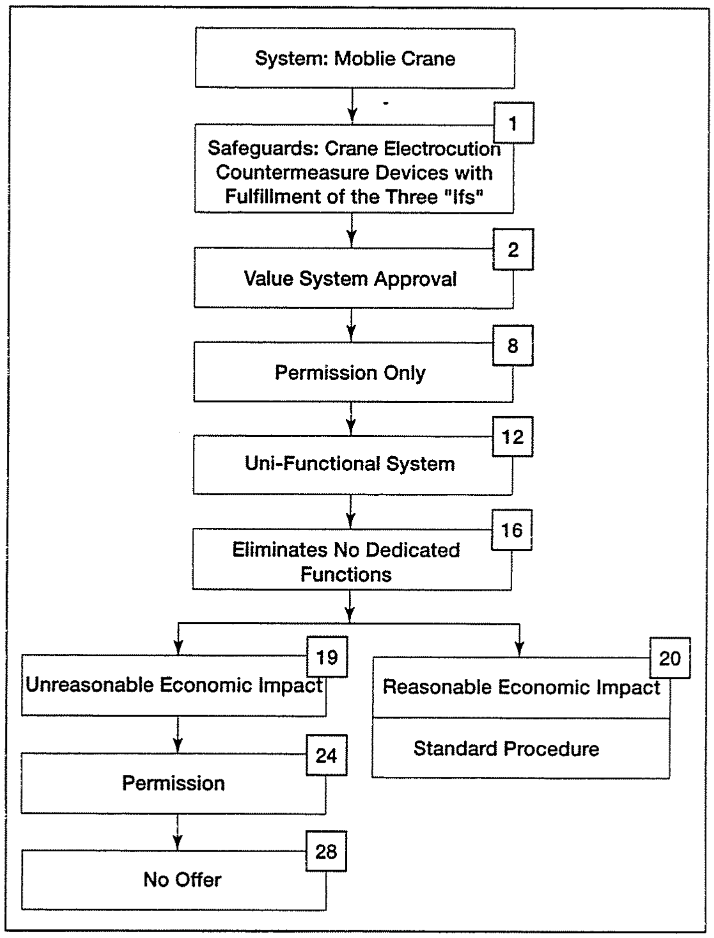

Figure 6. Decision process for mobile crane electrocution and shock safeguards

Example 7. Bowling Pinsetters

In the previous example, the quoted section of the standard contained the phrase "even if such devices are required by law or regulation." When the decision tree is applied to a specific locality where a law or regulation requires the candidate safeguard, the Shall Box [5] will prevail with its requirement that the safeguard be standard equipment. Local laws and regulations represent the local value system.

When various forums express different values, the protocol can be applied to each of them and the resulting collection of decisions can be used to make marketing judgements. As an example, one of the manufacturers of automatic bowling pinsetters developed a guarding system that was evaluated by Underwriters' Laboratories, Inc. In UL's judgement, the casualty hazards encountered during normal operations of the unit were "reduced to an acceptable minimum by the use of the guards." For many decades this standard guarding system has been used throughout the world with the exceptions of the states of California and Wisconsin which require as standard equipment an additional "special guard package." Although the special guards are described in all company manuals and are offered as optional equipment, no other forums have adopted them. The special guards are costly and impede certain maintenance procedures.

Using the following assumptions and observations, consider the application of the decision tree to the special guard package outside of California and Wisconsin:

a. No value system makes reference to the package.
b. The package is Type II; it helps or does nothing to the safety profile.
c. The costs attendant to the package have an unreasonable economic impact.

Under the stated scenario, the protocol follows precisely that illustrated in Example 1 where the "optional equipment" decision adopted by the manufacturer is one of the three choices advanced.

A different tactic would apply if the hazards addressed by the special guard package are not reasonably foreseeable. Here, the judicial value system *does not require safeguarding* because by its definition there is no safety problem. Thus, since the package does no harm, the guards would be classified as Type III; they neither help nor harm. The protocol would then move from [1] to [4] to [11] where we would be compelled not to offer the special guard package.

Example 8. Underride Guard

There is a class of cases where the candidate safeguard is an enhancement of an existing safety feature. For example, if it is desired to move from a safety factor of *three* to one of *five*, the candidate safeguard is the increase in the safety factor, *two*. Another example is provided by the underride guard that is used to prevent excessive underride of a passenger vehicle when it collides with the rear end of a heavy commercial vehicle (See Fig. 7). The resulting intrusion into the passenger compartment gives rise to a decapitation potential in addition to the normal injuries that result from collision forces imparted to the occupants.

The construction of underride guards is regulated by the Federal Highway Administration (FHWA) of the Department of Transportation. Specifically, Regulation 393.86 - Rear End Protection requires that:

"Every motor vehicle, except truck-tractors, pole trailers, and vehicles engaged in driveaway-towaway operations, the date of manufacture of which is subsequent to December 31, 1952,

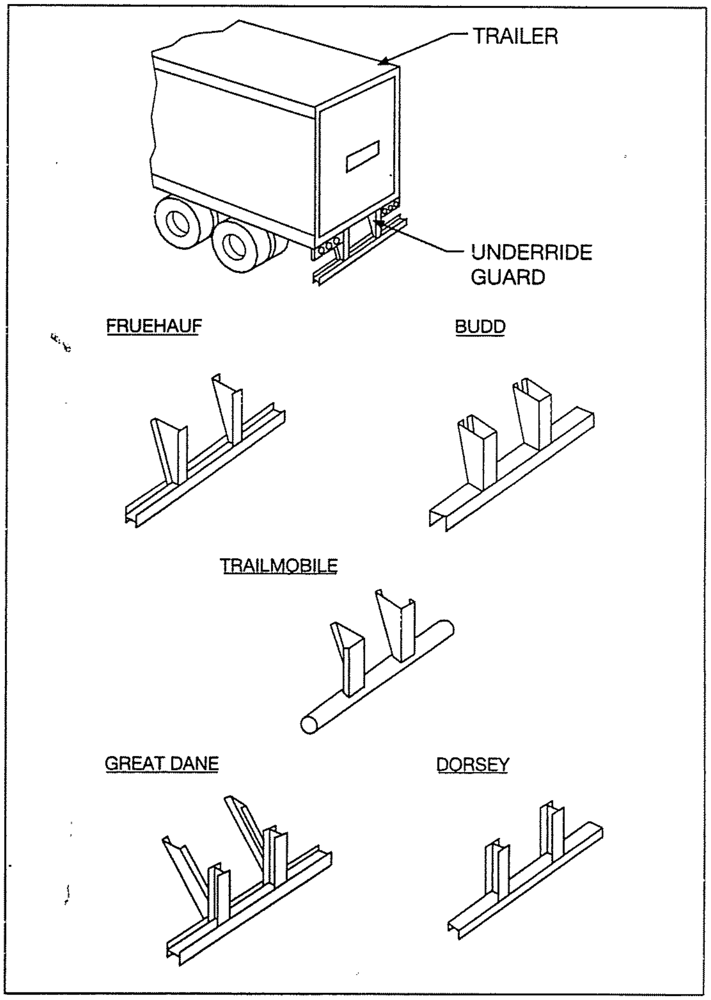

Figure 7. Current underride guards

which is so constructed that the body or the chassis assembly if without a body has a clearance at the rear end of more than 30 inches from the ground when empty, shall be provided with bumpers or devices serving similar purposes which shall be so constructed and located that: (a) The clearance between the effective bottom of the bumpers or devices and the ground shall not exceed 30 inches with the vehicle empty; (b) the maximum distance between the closest points between bumpers, or devices, if more than one is used, shall not exceed 24 inches; (c) the maximum transverse distance from the widest part of the motor vehicle at the rear to the bumper or device shall not exceed 18 inches; (d) the bumpers or devices shall be located not more than 24 inches forward of the extreme rear of the vehicle; and (e) the bumpers or devices shall be substantially constructed and firmly attached. Motor vehicles constructed and maintained so that the body, chassis, or other parts of the vehicle afford the rear end protection contemplated shall be deemed to be in compliance with this section."

Paraphrasing the structural integrity requirement, bumpers or devices shall be substantially constructed and firmly attached to afford the rear end protection contemplated. Note that the words *substantially, firmly,* and *contemplated* are never defined; surely this is rulemaking at its worst. Nevertheless, technologists have followed the spirit of the regulation and have produced the guards shown in Fig. 7. An amalgam of these guards was characterized by the FHWA as the "Current Guard"; its force-displacement property is defined in Fig. 8*i*. To proceed

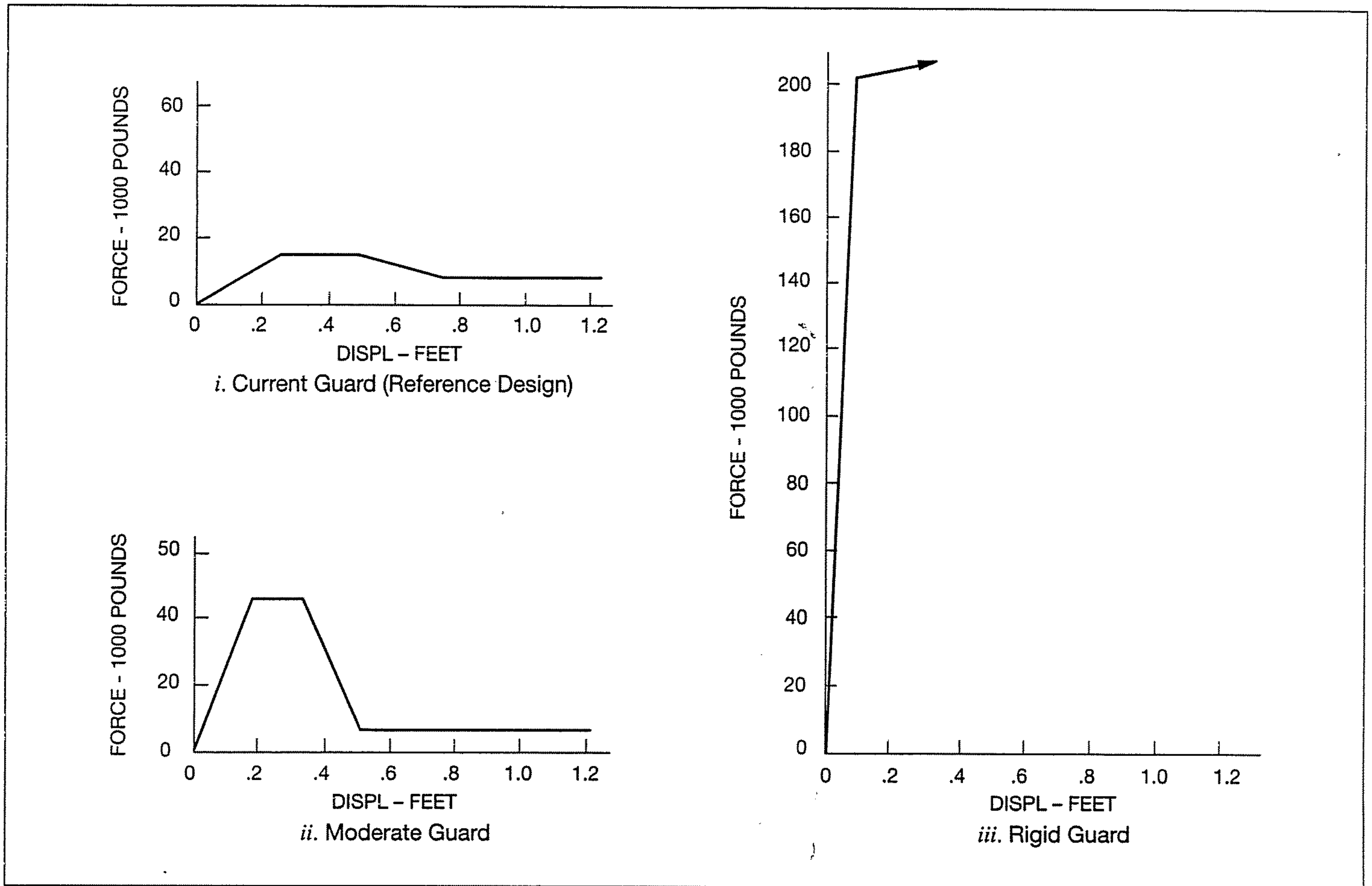

Figure 8. Force deformation properties for underride guards evaluated in the FHWA risk analysis

with our example, the system to be studied by the decision protocol is a truck outfitted with the "Current Guard." The candidate safeguards will be taken as the extra protection afforded by a "Moderate Load Guard" and a "Rigid Guard" which are characterized respectively by their load-displacement diagrams illustrated in Figs. 8*ii* and 8*iii*. Tomassoni and Bell report on a risk analysis performed by the FHWA on the three guards represented in Fig. 8.[8] Table 2 describes their benefit comparison. Both candidate guards improve safety by approximately 18% and both are considerably more costly than the "Current Guard."

The application of the decision tree begins by inserting the extra protection of the Moderate and Rigid Guards into Box [1]. No value system requires the *extra protection* which brings us to Box [4]. The *extra protection* is a Type I safeguard that always benefits; Box [9]. The truck/underride system is uni-functional [12] and eliminates no dedicated functions [16]; consequently, the decision tree takes the form shown in Fig. 9.

We observe that the final adoption strategy depends on whether the economic impact is reasonable or unreasonable. Recalling that the decision tree is not applicable to regulatory value systems, we can nevertheless inquire into the FHWA procedures for determining reasonable economic impact.

Lifetime cost estimates made by the FHWA included some of the following factors:

1. There are approximately four million vehicles that are underride candidates.
2. Initial cost of guards.
3. Added fuel cost related to the increased weight of the guards.
4. Guard maintenance.
5. Revenue loss due to payload displaced by the added guard weight.
6. Revenue loss due to decreased payload capacity caused by guards restricting the rear wheel sliders (1720 pounds of payload per foot of slider restriction).

In 1967 and again in 1977 the Department of Transportation initiated rulemaking efforts to improve protection for passenger car occupants. A number of underride guard concepts, including the Modified and Rigid Guards, were part of their studies. The 1967 efforts were terminated in 1971 when the Administrator of the National Highway Traffic Safety Administration concluded that the safety benefits achievable in terms of lives and injuries saved would not be commensurate with the cost of implementing the proposed rule. As of this writing, no modification of Regulation 393.86 has evolved from the 1977 study. It should be pointed out that the regulatory value system must wrestle with the difficult Cost/Benefit tradeoffs that ultimately involve placing values on human life and limb.

Returning to the determination of reasonable economic impact that must be made by the safeguard supplier in our underride guard example [20], all decisions are evaluated in the final analysis by the supplier's *perception* of the judicial value system. If the supplier believes that a jury will find the cost of preventing 150 fatal or serious injuries to be reasonable, Box [20] requires that the Moderate or Rigid Guard be included as standard equipment. A jury judgement of unreasonable economic impact [19] requires no departure from the Current Guard [28]. Voluntary measures such as optionalizing [27] or advising [29] are not precluded.

Guard Type	Predicted Fatal and Serious Injuries	Initial Guard Cost	Prevented Fatal and Serious Injuries	Increased Guard Cost
Current Guard	822	$50	–	–
Moderate Load Guard	682	$83	140	$33
Rigid Guard	669	$157	153	$107

Table 2. Benefit comparisons among candidate underride guards

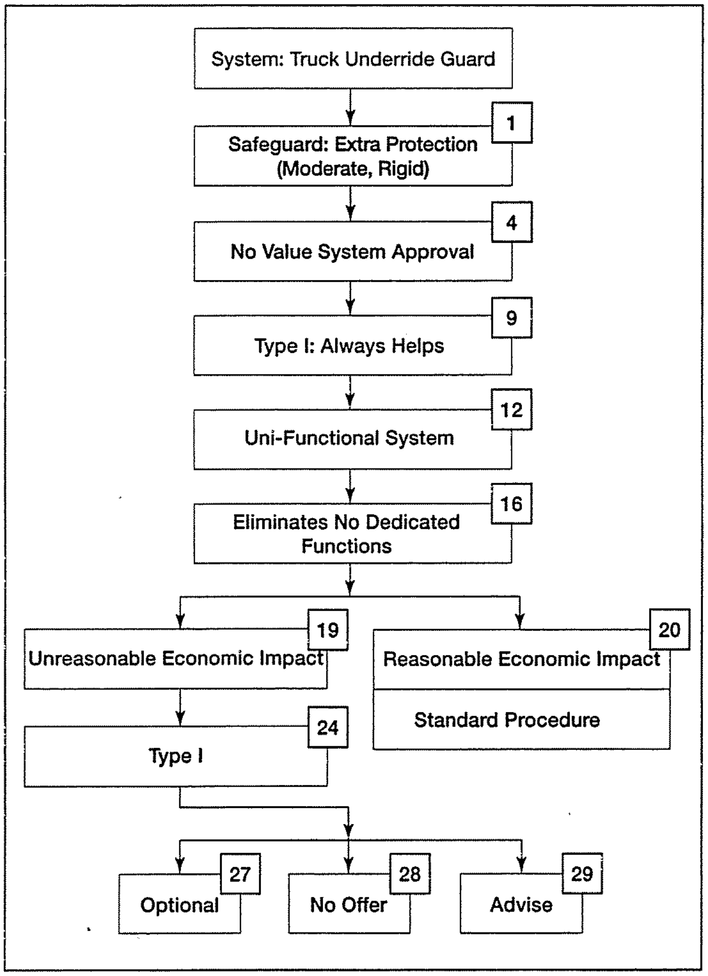

Figure 9. Decision process for truck underride guards

IV. CONCLUSION

The decision tree depicted in Fig. 1 is constructed using three safety philosophies that may be stated as follows:

1. Bend technology to the will of humankind while holding safety and cost paramount.
2. Private decisions to use safeguards that introduce new hazards should not be made.
3. The use of safeguards should comply with appropriate value systems.

To facilitate the application of these rules, two classification methods were employed that enable both *safeguards* and *systems* to be uniquely categorized. The Intrinsic Classification was used for *safeguards* and a dedicated/general purpose scheme was applied to *systems*.

The individual philosophical elements in the decision tree are all necessary conditions that must be followed. The array chosen to meet these necessary conditions is a sufficient condition, i.e., our decision tree, if followed, will meet all the required conditions. On the other hand, our decision tree is not unique, e.g., we may choose *economic impact* as our first screening procedure. Nevertheless, we have selected the screening order embodied in Fig. 1 because it goes from easy to hard; it leaves the most subjective category, reasonable economic impact, to last.

Support and partial corroboration of our decision making protocol can be found in another intellectual discipline; the judicial value system. A number of states have adopted the findings of Barker v. Lull Engineering Co. which first introduced the concept of risk/benefit as a liability criterion. Consider the following:

Barker v. Lull Engineering Co. 573 P.2d 454 (1978)

In this case the Supreme Court of California stated that, "a product may be found defective in design, so as to subject a manufacturer to strict liability for resulting injuries, under either of two alternative tests . . .

"1. a product may be found defective in design if the plaintiff establishes that the product failed to perform as safely as an ordinary consumer would expect when used in an intended or reasonably foreseeable manner.

"2. a product may alternatively be found defective in design, if the plaintiff demonstrates that the product's design proximately caused his injury and the defendant fails to establish, in light of relevant factors, that, on balance, the benefits of the challenged design outweigh the risk of danger inherent in such design. "Among the 'relevant factors' the jury may consider when weighing the benefits of the design against the risks, in the second test, are:

(a) the gravity of the danger posed by the challenged design;
(b) the likelihood that such danger would occur;
(c) the mechanical feasibility of a safer alternative design;
(d) the financial cost of an improved design;
(e) the adverse consequences to the product and to the consumer that would result from an alternative design."

We first observe in paragraph (1) that a distinction is made between expected use and reasonably foreseeable use. The same distinction is made in our discussion of general purpose multi-functional systems. Our second observation concerns the three "relevant factors" related to alternative designs. The mechanical feasibility factor given in paragraph (2c) is equivalent to functional evaluations in the decision tree leading to boxes [15], [16], [17], and [18]. The determination of reasonable economic impact corresponds to paragraph (2d) dealing with financial cost. Finally, the adverse consequences to the consumer referenced in paragraph (2e) is directly related to the Intrinsic Classification entries in boxes [10] and [11] that deal with safeguards with negative characteristics.

Various types of decisions are incorporated into the safeguard adoption protocol; namely,

- Standard Equipment
- Standard With Additional Equipment
- Do Not Use
- Optional Equipment
- No Offer
- Advise
- Ignore

A number of practitioners in the field of product liability have taken the position that "safety should not be optional." Whatever its jury appeal, this simplistic approach violates one or more fundamental philosophies that society has adopted for its safety and well-being.

In 1972 the Supreme Court of New Jersey decided the case *Bexiga v. Havir Mfg. Corp.* Their ruling imposed a non-delegable duty on manufacturers to supply safety devices where it is feasible to do so. Subsequently, many state courts adopted similar findings. Although the Bexiga litigation involved a small Havir power press (open back inclinable), the decision has general applicability. The court's finding was an intellectual disaster on two levels; the specific punch press technology and the general non-delegable duty concept. With respect to the Havir press, a technical misrepresentation led the court astray; namely, that a two button safeguard would be appropriate for any of the machine's normal uses. On this basis they concluded it should be standard equipment. Indeed, our decision tree would also make a universal safeguard standard equipment if it was economically practicable. It should be noted, however, that no universal safeguards exist for general purpose power presses, that the most advanced two hand hostage controls preclude many machine functions (see Example 2) and that the Havir press with its full revolution clutch could only have been supplied with a two hand activation device that would never qualify as a safety device by ANSI or OSHA criteria.

The New Jersey court made two additional findings relative to presses:

(1) "The Court stated that the trial judge properly precluded the question of whether responsibility for the absence of safety devices was chargeable to Havir from going to the jury. It reasoned, 'Since the machine could be used to perform various tasks it conceivably could require a different group of safety devices in connection with each task.' Thus, it held, '[T]he imposition of such a duty upon Havir would have been impractical and that it did not act unreasonably in not equipping the press with safety devices on its own.'

(2) "We hold that where there is an unreasonable risk of harm to the user of a machine which has no protective safety device, as here, the jury may infer that the machine was defective in design unless it finds that the incorporation by the manufacturer of a safety device would render the machine unusable for its intended purposes."

We note that the court's use of the word "impractical" corresponds to our characterization of *unreasonable economic impact*; the phrase "unusable for its intended purpose" corresponds to our designation *precludes some functions*.

The next level of philosophical mischief associated with "the non-delegable duty" is far more serious. The 1972 court treated all safeguards homogeneously as if they were Type I (always improve safety); the Intrinsic Classification System was not published until 1981. Would the court impose a common law duty to compel manufacturers to furnish as standard equipment safeguards that only compromise safety (Type VII) or that have no safety value (Type III and VI) or that may do more harm than good (Type IV and V)? The following excerpt from the court's decision demonstrates their commitment to public safety notwithstanding their insufficient technical understanding:

"Where a manufacturer places into the channels of trade a finished product which can be put to use and which should be provided with safety devices because without such it creates an unreasonable risk of harm, and where such safety devices can feasibly be installed by the manufacturer, the fact that he expects that someone else will install such devices should not immunize him. The public interest in assuring that safety devices are installed demands more from the manufacturer than to permit him to leave such a critical phase of his manufacturing process to the haphazard conduct of the ultimate purchaser. The only way to be certain that such devices will be installed on all machines — which clearly the public interest requires — is to place the duty on the manufacturer where it is feasible for him to do so."

On multi-functional machines whose applications are unknown to the supplier, the ultimate purchaser/user is the *only* one with the input information to maximize safety by the judicious selection of safeguards that exhibit no downside in a specific task. With reference to mechanical power presses, every known safeguard is a Type IV device that can compromise safety in the wrong application. The only responsible approach to the press safety problem is to appeal to users and not manufacturers to select and apply safeguards; this directly opposes the *Bexiga v. Havir* philosophy.

User safety involvement in the press industry has attained a high level of sophistication with the development of the "production system" methodology. The court's characterization of the ultimate purchaser's conduct as haphazard is inaccurate and reflects a very narrow view of manufacturing technology. Disciplined conduct of employers is compelled by regulatory law, statutory law and peer pressure; they are under pressure by worker's compensation carriers and unions and they are motivated by conscience, friendship and economics.

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PROFESSIONAL DEVELOPMENT

1. "Safety Analysis Methods for Farm Machinery," Agri-Component Exposition, Kansas City, MO, June 9, 1983.

2. "Product Liability: Theory v Practice," Greater Chicago Plastics and Allied Industries Council for the City of Hope, Niles, IL, November 16, 1983.

3. "The Analysis and Design of Mobile Crane Safety Systems," Grove Manufacturing Company, Shady Grove, PA, March 26-28, 1984.

4. "Safety and Human Factors Considerations in the Design of Electrodynamic Separators," Greater Portland Production Engineers, Portland, OR, June 2, 1984.

5. "How Long Should a Product Last?" American Society of Mechanical Engineers Design Engineering Education Committee; Chicago, Illinois; McCormick Place, March 3, 1987.

6. "Computer Programs for Design Engineers," American Society of Mechanical Engineers Design Engineering Education Committee; McCormick Place, Chicago, Illinois, March 3, 1987.

7. Oakton Community College, Des Plaines, Illinois; Fundamentals of the Internet, course no. WWW 111; August to December, 2004

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Seminar: "The Analysis and Design of Mobile Crane Safety Systems," Grove Manufacturing Co., Shady Grove, PA, March 26, 1984. Topic: Insulated Links for Cranes.

Seminar: "Lockout-Tagout During Machine Maintenance" - American Contractors Insurance Group. Triodyne Inc., Niles, Illinois; September 13, 1996.

Guest Lecturer: ASME Student Chapter; Notre Dame University, South Bend, Indiana; November 4, 1996. Topic: "The History and Development of Automated Pinspotting."

Seminar: "Construction Crane/Overhead Powerline Contact" - Construction Industry Manufacturers Association. Triodyne Inc., Niles, Illinois; December 11, 1997

STANDARDS COMMITTEES

1. Title: Accredited Standards Committee ASC-A14, Safety Codes for the Construction, Care and Use of Ladders.
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2. Committee: American National Standards Institute A14.7, Mobile Ladder Stands and Ladder Stand Platforms
   Member: August, 2004 to Present

3. Committee: American National Standards Institute A14.8, Ladder Accessories
   Member: November, 2004 to Present

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American Society of Mechanical Engineers - Associate Member through 2004
American Society of Safety Engineers – Member through 2004

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	Duration:	June 1984 - November 1984
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	Position:	Automatic Pinsetter Mechanic
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	Business:	Bowling Equipment Design and Manufacturing
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	Duration:	June 1979 - August 1979
	Duties:	Participated in an automatic pinsetter parts cost-reduction project, and assisted in the preliminary development of modifications to reduce pinsetter power consumption. Preparation of engineering drawings compatible with computer-aided manufacturing processes.
7.	Employer:	Gage Park Recreation Center, Inc., Chicago, Illinois
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Testimony given by William G. Switalski since January, 2002:

Crouther v. Littell, Inc.	Illinois	November 26, 2002
Ferriera v. Vulcan Engineering	Wisconsin	April 3, 2003
Triplett v. The Schebler Co.	Illinois	September 24, 2003
Steiger v. Edward Rose Development Co., et al.	Michigan	October 9, 2003
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Cole v. Stiles Machinery, Inc.	Michigan	November 24, 2003
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Shoemake v. Wexxar Packaging Inc.	Illinois	November 10, 2004
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